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DEALING WITH TECHNICAL PROBLEMS
RELATING TO THE PRODUCTS, PROCESSES AND INVESTIGATIONS OF
N.V. PHILIPS' GLOEILAMPENFABRIEKEN

EDITED BY THE RESEARCH LABORATORY OF N.V. PHILIPS' GLOEILAMPENFABRIEKEN, EINDHOVEN, HOLLAND

INTRODUCTION

With the appearance of the first number of "Philips Technical Review" after the liberation of the Netherlands an introduction from the editors is called for.

During the occupation we endeavoured to continue the edition of this Review as long as possible, but in the beginning of 1942 its further publication was prohibited. The Dutch edition was allowed to continue till July 1942, but was then also stopped. As a consequence the seventh year (1942) only of consists six numbers. These six numbers, which did not appear in the English edition, will be made available as soon as possible, in order to make the contents of the Review the same in the various languages.

At this moment of the reappearance of the Review we remember the black years which have passed and wish to pay tribute to all those members of our Philips community who lost their lives, as victims of the war, injustice and atrocities among whom we regret to announce one of the regular contributors to this Review, G. Heller.

For fresh readers, who up till now have not known Philips Technical Review, it is well to state here that the object of this periodical is to give information on the properties and applications of the various products of N.V. Philips' Gloeilampenfabrieken at Eindhoven and to elucidate all problems connected therewith. Especially it is directed to the engineering world and to other technically-minded users of our products; it is not intended as an advertising journal. Although mathematics are applied, where nesessary, a clear manner of representation is always the principal aim.

Although in this Review the results of scientific research are mentioned, it should not be considered as an organ for the publication of scientific papers. For those who are interested in the researchwork accomplished in the Philips Laboratories it should be noted that the results of this work are published in a new journal, "Philips Research Reports", the first number of which appeared in October 1945; these reports are only edited in the English language.

We hope that with its reappearance "Philips Technical Review" will receive in a broad circle of readers the same attention as in former years.

THE EDITORS.

SINTERED GLASS

by E. G. DORGELO.

666.189.4

In the manufacture of certain articles in which many metal parts (*e.g.* leading-in wires) must be fused into glass close to each other, it is sometimes impossible, due to the too low fluidity of the molten glass, to force the drop of glass between the metal parts. In such a case glass in powder form can be used, and this can be introduced between the metal parts before fusing. The glass obtained after fusing, which is not completely clear, is called sintered glass, and contains many very small air bubbles. In this article various properties and possibilities of this glass are discussed.

In the manufacture of incandescent lamps, electronic and gas-discharge tubes different special kinds of glass are used, which must satisfy certain requirements for each type of valve or lamp, and therefore may differ very much from each other. A kind of glass whose properties and constructive possibilities are particularly favourable for one type may be quite unsuitable for another type.

For the development of a new lamp or valve, therefore, the possibilities offered by different kinds of glass should be subjected to an extensive investigation. If the existing kinds of glass are unsuitable for the application in view, an attempt is made to find a new and better kind of glass. In the case of different types of valves the progress of their development depended almost exclusively on the manufacture of a suitable new kind of glass.

One example is the sodium lamp covered on the inside with borate glass [1]), which is resistant to sodium vapour; further the high-pressure and super high-pressure mercury lamps, where it was necessary to find types of glass for the covering of the metal leads through the quartz [2]). In the development of transmitting valves for very short waves use was also, successfully made of special new kinds of glass, the electrolysis-free glasses [3]).

While in the examples mentioned here the new glasses are distinguished from the older ones by their chemical composition, in the case of "powder glass" an attempt has been made to create new possibilities by a modification in the physical structure. The stimulus for this attempt lay in a difficulty which occurs in the manufacture of articles in which many metal parts (for example leading-in wires) must be fused into glass close to each other. The liquid glass must then be forced between the metal parts, and the method fails when the spaces between are so small that a drop of molten glass, even under high external pressure, cannot penetrate sufficiently far into them, perhaps because of the fact that cooling takes place too rapidly as a consequence of the heat conduction through the metal parts. This difficulty can be overcome if, before the fusing in, the glass in fine powder form is introduced directly into the space where it belongs, the whole then being heated to a temperature at which the glass melts. The structure of the somewhat turbid sintered glass which is obtained upon fusing the powder is not homogeneous; it contains numerous very small gas or air bubbles which more or less modify the different properties of the glass. In general these changes are not of prime importance. Nevertheless, they may sometimes make possible constructions which are impossible with normal glass. Examples of such cases where preference is given to powder glass will be given later in this paper.

Sintered glass offers great advantages in the manufacture of valves and lamps for experimental purposes, due to the rapid and simple manner in which almost any desired lamp base can be made. Metal leads can be fused in at the same time that the base is made, while the process can be used for every kind of glass, including the kinds which are very difficult to soften.

The employment of sintered glass

The raw material, powdered glass, is obtained by grinding up pieces of glass. This powder is cast in a mould in which the metal parts to be fused in are already present. Care must be taken that the glass powder fills up the spaces well between the metal parts. After covering the mould the whole is heated to a temperature at which the glass is very fluid, so that only slight pressure is enough to fill even the smallest cavities.

The coefficient of expansion of the material of the mould must be adapted in a certain way to that of the glass. The wall of the mould must not clamp the solidified glass article; the coefficient

1) Philips techn. Rev. **2**, 87, 1937.
2) Philips techn. Rev. **3**, 119, 1938.
3) Philips techn. Rev. **6**, 255, 1941.

of expansion of the material of the wall of the mould must therefore be smaller than that of the glass. The bottom of the mould (which is separate from the wall) must, on the other hand, have by preference the same coefficient of expansion as the glass, since otherwise there is a danger that, upon cooling, any leads and the like which are fastened into the bottom will be bent. A mould which possesses the properties mentioned is shown in *fig. 1*.

Besides lead-pins, differently shaped objects can also be fused in, for instance metal strips, tubes, nuts, etc. (*fig. 2*). The number of pins, the distances between them and their grouping is subject to practically no limitations when sintered glass is employed. *Fig. 3* illustrates the great variety possible.

Fig. 1. Mould of metal with separate bottom and cover.

Furthermore it may be pointed out that simultaneously with the fusing-in of leads in a lamp or valve base the glass envelope can also be welded on. This envelope is then placed in the mould before the fusing of the powder glass base; the upper part of the mould must then be removed. In this way the separate welding process is eliminated. This process is, of course, subject to the restriction that it can only be applied in those cases where the electrodes inside the envelope are resistant to the heat radiation of the glowing mould. The tubes and bases shown in the photographs *fig. 4* are made in this way. It is obvious that other glass parts, such as an exhaust tube, can be welded in simultaneously with the fusing of the valve or lamp base (*fig. 5*). To prevent the exhaust tube from collapsing during the fusion, it is previously sealed at the bottom and filled with fine sand, which is shaken out after the fusion.

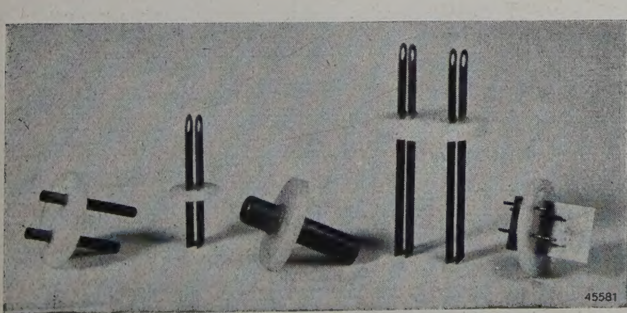


Fig. 2. Fused-in metal tubes and strips in powder-glass bases for valves.

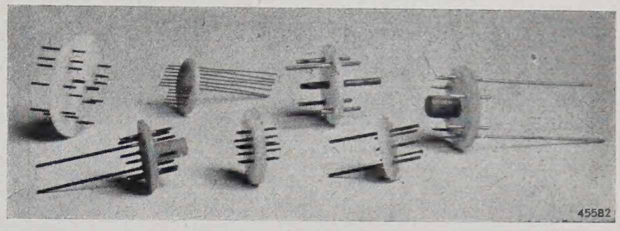
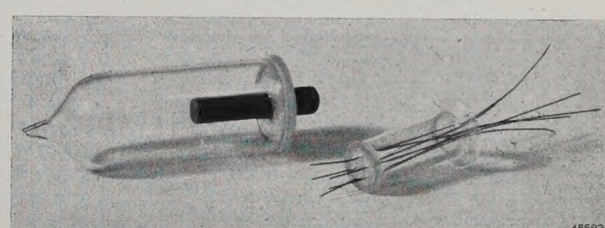


Fig. 3. The leads can be fused-in through sintered glass bases in almost any number and arrangement.

A special manner of fusing in, which is impossible with glass envelopes, can be applied to metal envelopes by strongly heating the edge of the metal envelope and then pressing it into the likewise previously heated sintered glass base. The projecting edge can be removed later. In this way it is possible, for example, to fasten lead-glass discs into an iron can. Because of the fact that the coefficient of expansion of the iron is larger than that of the glass, the iron upon cooling is clamped around the glass, giving a very reliable connection [4]). Nor is it of importance in this method whether the cross section of the envelope is a true circle.



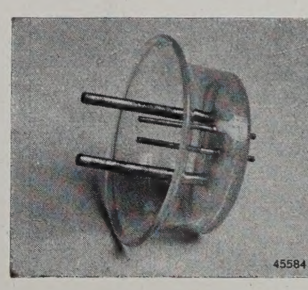


Fig. 4. Envelope and pinches, the powder-glass bases of which are welded to the envelopes at the same time that the powdered glass is fused.

Properties of powder glass

1) *Specific weight*

The circumstance that there is a very large number of small gas bubbles in sintered glass affects different properties; it is clear that for example the specific weight is smaller than that of

[4]) In principle this method of fusing-in is also possible with discs of clear glass.

the original glass. The decrease depends upon the size and the number of bubbles and is usually of the order of magnitude of 5 to 10 percent; with very fine powder the decrease is greater. The diameter of the bubbles usually lies between 10 and 50 μ. The number of bubbles per mm³ amounts to several thousands.

2) *Electrical properties*

When a block of powder glass is situated in an electric field the field strength in the glass will be much smaller than in the gas or air bubbles, as a result of the very different dielectric constants (glass: approx. 7, air: 1). The field is thus concentrated in the bubbles.

If we consider a piece of clear glass with only a few large air bubbles, the field concentration in these bubbles may be so high that the enclosed gas becomes ionized, which may lead to complete breakdown. Glass for high-voltage apparatus (X-ray tubes, for example) must thus satisfy the requirement of being free of bubbles to a high degree.

The situation becomes quite different when the air in the glass is divided into very many small bubbles. The potential difference between the boundary surface is then uniformly distributed over the numerous intermediate gas bubbles, so that the potential difference per gas bubble is so low that danger of ionization is out of the question. With powder glass indeed values of the breakdown voltage are found which are just as high as those measured on glass which is free of bubbles.

The electrical field in a medium in which there are globular gas bubbles can be calculated [5]). Different electrical constants of powder glass, such as the electrical conductivity λ', the dielectric constant ε' and the angle of loss, determined by $\tan \delta'$, can be calculated from the corresponding values for the homogeneous glass (λ, ε and $\tan \delta$). Thus if

$$p = \frac{\text{volume of all air bubbles}}{\text{total volume}},$$

we find that:

$$\frac{\lambda'}{\lambda} = \frac{2-2p}{2+p} \approx 1 - \frac{3}{2}p + \dots \quad (1)$$

$$\frac{\varepsilon'}{\varepsilon} = \frac{2\varepsilon+1-2p\ (\varepsilon-1)}{2\varepsilon+1+p\ (\varepsilon-1)},$$

which, *e.g.* when $\varepsilon = 7$, gives

$$\frac{\varepsilon'}{\varepsilon} = \frac{5-4p}{5+2p} \approx 1 - \frac{6}{5}p + \dots \quad (2)$$

$$\frac{\tan \delta'}{\tan \delta} = \frac{2\ (5-3p)}{10-3\ p} \approx 1 - \frac{3}{10}p + \dots \quad (3)$$

The formulae are valid only when $p \ll 1$. In order to obtain an impression of the influence which the air bubbles have on the constants mentioned we substitute $p = 0.1$. Then $\lambda'/\lambda = 0.85$, $\varepsilon'/\varepsilon = 0.88$ and $\text{tg}\ \delta'/\text{tg}\ \delta = 0.98$.

A further lowering of the values of ε' and λ' can thus be obtained by distributing much air among many small bubbles. For this purpose it is necessary to start with very fine powder and during the fusion the temperature must be raised very rapidly to prevent the escape or flowing together of the air bubbles. By the addition of substances which give off gas the percentage can be very much increased, which, however, involves a lowering of the strength of the glass.

3) *Thermal properties*

The heat conduction in sintered glass shows almost the same variation with p as the electrical conductivity (see formula 1). The heat conductivity of powder glass is thus somewhat less than that of

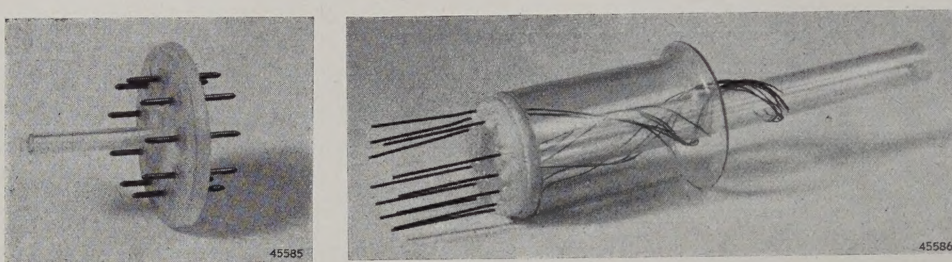


Fig. 5. Exhaust tubes can be welded in simultaneously with the fusing of the lamp or valve base.

[5]) K. W. Wagner, Archiv für Elektrotechnik, **2**, 382, 1914.

clear glass of the same composition. It is sometimes necessary to take special precautions in fusing because of this fact.

The coefficient of expansion of powder glass is the same as that of normal glass; the coefficient of expansion is not changed by the presence of air bubbles, which is a result of the well-known fact that a hollow body expands as if it were massive.

4) *Tensions*

Objects built up of more than one different material with different coefficients of expansion are not in general free of mechanical tensions at every temperature. This holds also for the welding together of two kinds of glass and for the introduction of a metal lead through glass. The occurrence of tensions in a glass object often leads to breakage and therefore methods have been developed for the checking of this. The tensions make the glass optically anisotropic and give rise to phenomena of double refraction, which can for instance be made visible with a polarization apparatus.

In this investigation of tensions it has now been found to the advantage of sintered glass that in objects manufactured with the help of this glass fewer mechanical tensions occur than in ordinary clear glass. This can be demonstrated by fusing together in pairs discs of different kinds of glass. When the discs fused together consist of powder glass smaller tensions appear after cooling than when the two discs are composed of the corresponding kinds of clear glass.

The explanation of this phenomenon is probably as follows. Since the solidification is accompanied by a decrease in volume, tensions will appear in the glass which are smaller the better the still soft glass is able to accommodate itself.

Now this is more easily possible in sintered glass than in clear glass of the same composition. If there is a large number of gas bubbles in the glass, as long as the surrounding glass is still somewhat soft they can compensate the volume decrease of the solidifying glass by expanding. This conception is thus based upon the fact that some parts of the piece of work become solid before the rest. This phenomenon often plays a part when metal components are fused in.

Completely homogeneous objects can also be made free of tension when normal glass is used by taking care that they are cooled very slowly. One of the advantages of sintered glass is that there is no objection to the cooling taking place more rapidly.

Applications

One of the chief applications of powder glass is in lamps and tubes for experimental purposes. However, it also offers a number of advantages for other applications which in many cases are important. In the following we shall mention several of them.

1) *In tubes with complicated electrode systems*

As already mentioned, the glass can be introduced into the mould in the form of finely divided powder so that it can easily fill all the small cavities. Complicated pieces of work, such as lamp bases with very many leading-in wires or with leads very close to each other can be made of powder glass without much trouble (see fig. 3). The freedom of choice in distance between the leads makes it possible to place them in such positions that the simplest and most logical assembly of the electrode

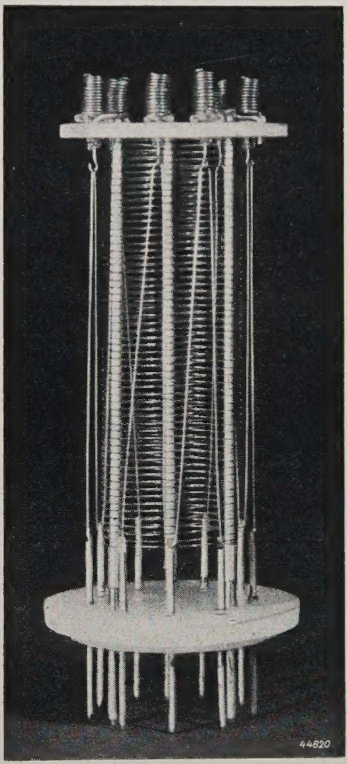


Fig. 6. Electrodes of a transmitting valve for short waves assembled directly on the powder-glass base.

system is achieved. Thus in *fig. 6* may be seen the grid-cathode part of a short-wave transmitting valve, in which the two electrodes are welded directly to the leads. These leads form two concentric circles with diameters corresponding to those of the cathode and grid. Such a construction excels in simplicity and sturdiness, while the slightness

of the self-induction of the lead elements makes possible a satisfactory functioning on short waves. In extreme cases, in order to keep the selfinduction as low as possible, it is possible to lead the electrode itself through the glass. Three examples are shown in *fig.* 7 (see also fig. 2).

In the left-hand valve there are two electrodes bent in a U-shape which pass through the glass base while retaining their cross section. The self-induction of the lead part is very small here. At the same time good cooling is hereby obtained. In the case of the middle valve a shielding plate separating the two parts of the valve is led through the base.

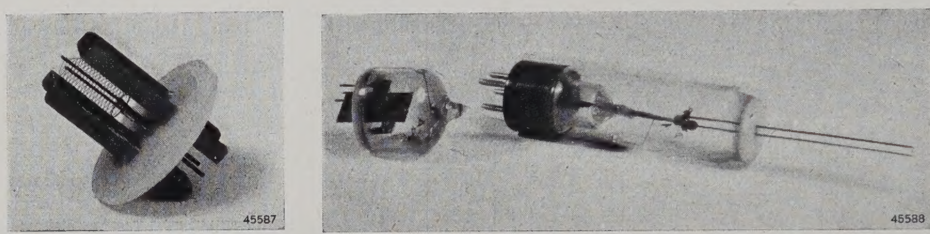


Fig. 7. Several transmitting valves for very short waves in which the electrodes themselves are fused into the base.

The right hand valve of fig. 7 contains two leads in the form of strips which together form a Lecher system. Experience has shown that with clear glass and the ordinary pressing technique such constructions are only made reliable with difficulty. It is difficult to obtain a satisfactory distribution of the drops of glass. At the edges of the metal also the tensions are often too high, so that the valve cracks at that spot.

In the case of powder glass the first difficulty is non-existent, while less hindrance is experienced from the second.

2) *Crowded constructions*

Such constructions often result in high temperatures of the glass wall. It is then necessary to have recourse to glass with a high softening point. Normal boro-silicate glasses with a softening point of 500-600° C are often too soft or are too poor insulators at the high operating temperatures, so that harder glasses must be used. As a rule these glasses cannot be pressed into narrow interstices in the ordinary way. Before the necessary pressure is reached the drop of glass has cooled off too far. The pressing in of metal parts directly is even more difficult. Due to the fact that pressing is unnecessary in powder technique, high requirements need not be made of the mould, and it can be heated to such a high temperature that even a very hard glass still becomes sufficiently fluid. It has hereby become possible to make lamp bases of kinds of glass, such as the so-called electrolysis-free glass, which could not formerly be so used and this again has opened the possibility of constructing new types of valves, especially in the field of transmitter valves for decimetre waves.

3) *Connecting seals*

It is possible to fill the mould with layers of powdered glass having different properties, and then to fuse the whole. By choosing powdered glasses of gradually increasing coefficients of expansion graded seals can be made, *i.e.* tubular parts which at one end can be fused to a glass with a high coefficient of expansion and at the other to a glass with a low coefficient of expansion.

Another possibility offered is that the base of a valve which is to contain the vapour of an alkali metal can be protected by a thin layer of resistant glass. It is well known that most kinds of glass are very severely attacked by such vapours. In the case of glasses containing lead for example such a strong reduction takes place that the glass turns black, due to the liberated lead. Now by first scattering powdered lead glass in the mould and over it a thin layer of borate glass, a protecting layer is formed. Borate glass is not attacked; it cannot, however, be used alone, since the temperature interval in which softening takes place is particularly short. A variant on the foregoing is the use of glasses of different colour, by which means all kinds of indications can be introduced on the object.

4) *Rapid fusing-in and cooling*

Notwithstanding the fact that the conduction of heat in sintered glass is smaller than in the corresponding clear glass, it appears in heating

that with sintered glass without many precautions a more equal heating through the whole object is obtained. Probably the numerous gas bubbles present in sintered glass ensure that during the heating the radiation of heat is strongly dissipated. One result of this is that the so-called pre-heating which precedes the fusing of a lamp base to the envelope can take place quite rapidly without cracking the tube. It is clear that this is of great importance in mass production. The annealing also can in most cases proceed quite rapidly due to the previously mentioned great elasticity of the still not completely solidified powder glass, so that the occurrence of large tensions is combated.

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50 YEARS X-RAYS

In November 1895 Wilhelm Conrad Röntgen, professor at the university of Würzburg, made his first observations on X-rays; his publication is dated December 27th 1895 and entitled: "On a new Kind of Rays", and it was a communication to the "Würzburger medizinisch-physikalischen Gesellschaft" (1895, p. 137—141).

Now, 50 years afterwards, the whole world is going to commemorate this important contribution to our present day scientific insight — and to our medical and physical instruments.

To look backward on the road achieved during these 50 years is indeed worth while. There the interaction is reflected which took place between the various developing branches of science and technique, and it is possible to find there how an amazing quantity of work has given life to a series of most important practical applications of X-rays. These are too well known to be summed up here, but they engendered, too, a great array of very elaborate apparatus. The Philips' Factories and Laboratories have also had their part in this development. Here it may suffice to refer to the 38 publications which appeared in the first seven years of this periodical on the subject of X-rays and their applications: 9 of these articles dealt with X-ray tubes and X-ray apparatus; 21 on applications and 8 on the methods used in these applications. In this number, too, with which the Philips Technical Review re-enters the world, after the forced interruption during the German occupation, the reader will find a description of an X-ray apparatus which in many respects is representative of the ideas and methods which have developed in the domain of X-rays.

In the 1946 volume of this journal we hope to find from our X-ray Department still more contributions on the development of special tubes, apparatus and methods of research. Thus the great discovery of W. C. Röntgen 50 years ago will be given worthy commemoration.

AN X-RAY APPARATUS FOR CONTACT THERAPY

by H. A. G. HAZEU, J. M. LEDEBOER and J. H. v. d. TUUK. 261.386.1: 615.849

In the X-ray treatment of tumours on the surface of the skin it is desirable, in order to spare the underlying healthy tissue, that the radiation intensity should decrease rapidly with increasing depth below the skin. In order to realize this it is necessary that the distance between the source of X-rays and the skin should not be too large (often there exists immediate contact between X-ray tube and the skin, hence the name contact therapy) and the X-ray tube should possess only a slight "own filter". In order to satisfy these and other requirements connected with medical practice, the tube of the Philips contact therapy apparatus is so constructed that the X-radiation leaves the tube through an opening in the earthed cathode. This construction is described in detail in the following paper; it permits an irradiation from a distance of 18 mm of the focus with a filter equivalent to only 0.2 mm of aluminium. The tube is fed with 50 kv DC voltage at a current of 2 mA and possesses forced air cooling. The X-ray intensity on the skin is so high that an irradiation time of a few minutes is usually sufficient. This type of therapy is thereby made accessible to a much wider circle of patients than is possible with radium treatment.

Depth therapy and surface therapy

The treatment of tumours with radium or X-rays depends upon the fact that the affected tissue is attacked by these rays and if a sufficient dose is administered this tissue will die off. However, the healthy tissue around the tumour is, also more or less exposed to the X-rays and attacked by them. If this impairment is too severe, the healing of the diseased tissue can be retarded or even prevented. The aim of the doctor, therefore, must be to make the ratio of the radiation dosage on the healthy tissue to that on the diseased tissue as small as possible. The measures to be taken for this purpose are quite different according as the diseased tissue lies deep below the surface of the skin or is situated only slightly below or on the surface of the skin.

Let us first consider the first case of "depth therapy". Since the intensity of the X-rays decreases with the square of the distance from their source, and, moreover, since the rays suffer an attenuation in the tissue, the intensity will be smaller at some depth than on the skin. The dosage has a certain depth gradient, see *fig. 1a*. In depth therapy, therefore, the diseased tissue always receives a smaller dose than the healthy one at the surface. The fact that a healing effect can nevertheless be obtained is due to the fact that the diseased tissue is sometimes more severely attacked than the healthy tissue by the same dose. In fig. 1a the relative positions are indicated of the dose required for killing the diseased tissue and the dose permissible with the object of sparing the healthy tissue. It may be seen that with these relative positions therapy is possible, but only when the radiation does not have too great a depth gradient. In depth therapy, therefore, the smallest possible depth gradient of the radiation is desirable.

The situation is quite different in the case of tumours on the surface of the skin, *i.e.* in "surface therapy". In this case the healthy tissue, which will also be exposed upon irradiation, lies for the most part under the diseased tissue, the positions being thus reversed. This case is naturally more favourable for radiation therapy, since here the diseased tissue always receives a larger dose than the healthy

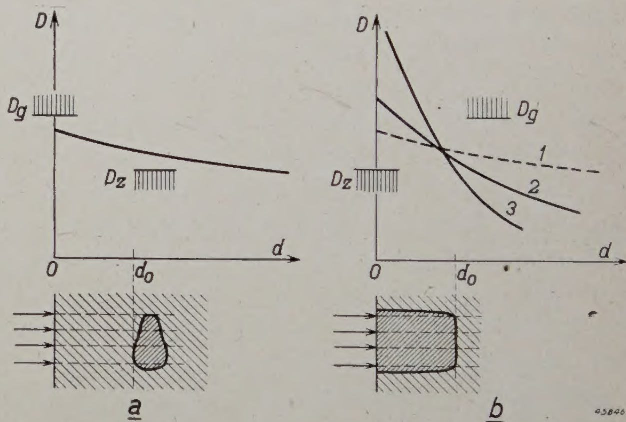

Fig. 1*a*) In depth therapy the dose of X-rays administered on the surface of the skin where the tissue is healthy may not exceed a value D_g, while at a depth d_0 under the skin, where the diseased tissue is situated, it must attain at least a value D_z. The smallest possible depth gradient of X-ray intensity is required.

b) In surface therapy a minimum value D_z is required on the surface and a maximum value D_g at the depth d_0. Here a steep depth gradient is favourable, for instance one according to curves *2* or *3*, which are much steeper than the broken line curve *1* representing the curve of fig. 1*a*.

tissue. If we now indicate the required minimum dose on the diseased and the maximum permissible dose on the healthy tissue (*fig. 1b*) it is clear that in principle any depth gradient of the dose can be used. In order, however, to spare the healthy tissue as much as possible, it is clear that a fairly steep depth gradient is preferable, while one

also has the possibility of administering a larger dose on the diseased tissue.

How is it now possible to realize the desired slight or steep depth gradient, as the case may be? The gradient is characterized by comparing the intensity of radiation at the surface of the skin I_h with the intensity I_d at a depth d under the skin. If a is the distance from the source of X-rays (focus of the tube) to the skin and μ the coefficient of attenuation of the tissue for the rays, the square law gives

$$\frac{I_d}{I_h} = \frac{a^2}{(a+d)^2}\, e^{-\mu d} \quad . \; . \; . \; . \; . \quad (1)$$

This "depth quotient", which is a measure of the depth gradient, becomes large (*i.e.* approaches the value unity) when a is large compared with d and if μ is small. In depth therapy, therefore, the X-ray tube will be set up at some distance from the patient (30 to 100 cm) and hard radiation (short wave length) will be used, as it is only slightly attenuated in the tissue. This means high tube voltages [1] — practically usually 200 kV, sometimes up to 1000 kV — and the employment of a heavy metal filter to suppress the soft parts of the mixture of radiation emitted from the focus. In order to obtain the desired dose in the tumour without too long an exposure time in spite of the great distance and the loss of radiation in the heavy filter, a high tube power (1-4 kV) is needed.

In the case of surface therapy, where the object is a low depth quotient I_d/I_h, exactly the opposite measures must be taken: the distance a between focus and skin will be made as small as possible and radiation will be used which is subject to great attenuation in the tissue, thus soft radiation (low tube voltage, approximately 50 kV) without more filtering than is inevitable due to the passage of the radiation through the wall of the tube (so-called own filter of the tube).

Apart from the fundamentally more favourable situation in surface therapy compared with depth therapy, there is also the extra advantage that, thanks to the small distance from focus to object and the weak filtering, only a low tube power is necessary for the required dosage. The X-ray tube may therefore be small and easily adjustable, the whole apparatus may, also because of the ralative low tube voltage, be light, even portable, while in addition very short exposure times are sufficient.

These favourable aspects of surface therapy, or "contact therapy" as it is often called, the X-ray tube being in immediate contact with the patient's skin, have contributed much to the adoption of the X-ray treatment of skin diseases and surface tumours.

In the following description of the Philips CT apparatus, which has been specially developed for this therapy (CT), we shall enter into more detail about some of the aspects of this therapy [4]).

Construction of the X-ray tube

From the above it follows that an X-ray tube for contact therapy must fulfil the following requirements:

1) The distance from the focus to the window must be very short in order to make it possible to place the focus close to the skin.
2) The filter of the tube must be small, which means that the window of the tube at the spot where the rays pass through the tube wall must be very thin and made of a light material (low absorption).

In addition to these there are several practical requirements which emerge from the desire to be able to apply contact therapy to tumours and diseases of the mucous membrane in cavities of the body, such as the mouth, throat, etc. For this purpose the focus should be close to the end of the tube and this end should be small enough to be introduced into such cavities. At the same time it is usually desirable that the radiation should be emitted in a forward direction (not lateral, as is customary).

The requirement of a thin tube with the focus at the end also holds in the employment of X-rays for the testing of material, when tubular casts and the like are examined. For this purpose X-ray tubes have been constructed with a hollow, earthed anode projecting from the tube and shaped like a funnel [2]), see *fig. 2.* For our purpose, however, this construction has the disadvantage that the second requirement mentioned, small own filter, cannot easily be satisfied. The rays, which are emitted in the direction of the length of the tube, must pass through the anode plate upon which the focus (lozenge) is situated. For the sake of high efficiency the lozenge must consist of a heavy metal, usually tungsten; this metal, however, also has a high absorption, especially for the soft rays. Moreover,

[1]) See: Philips techn. Rev. 4, 161, 1939. It should also be noted that until now it has not been determined whether the healing effect for tumours is fundamentally different for X-rays of different wave lengths corresponding to tube voltages between 50 and 1000 kV. The choice of wave length can therefore, apart from technical considerations, be determined primarily by the desired depth gradient.

[2]) *Cf:* Philips techn. Rev. **5**, 69, 1940 (fig. 6). For a contact therapy tube of this kind see H. W. Ernst, K. Frik and P. Ott, Strahlentherapie **52,** 369, 1935.

the anode plate must not be very thin, since it must be resistant to the strong heat transfer by the current of electrons and must also be vacuum tight. In this way a heavy own filter is obtained and in consequence a much harder and less intense radiation than is desirable.

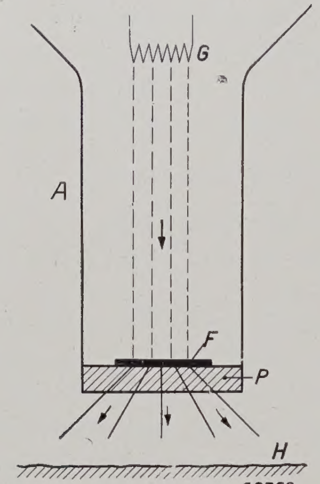

Fig. 2. Construction of an X-ray tube with earthed anode projection. The electrons emitted from the filament G move through the earthed hollow anode A and impinge upon the copper plate P. The upper layer of this plate, the lozenge, upon which the focus F is formed, consists of tungsten. The X-rays emitted by P must pass through the anode plate P to reach the surface to be irradiated H.

Of course these two objections can be partially compensated by making the distance between focus and skin very small. When the distance is small enough (several mm) it is possible to work with both hard and soft radiations, as is indeed the case with radium irradiation, since then, due to the dominance of the factor $a^2/(a+d)^2$ in equation (1), a very steep depth gradient is nevertheless obtained. Working with such small distances has in turn, however, other objections. In the first place very small variations in the distance then have immediately a great influence on the intensity on the skin, so that dosage is made difficult. Especially, however, at such small distances it is necessary to use very large angles of divergence of the beam of the X-rays. The peripheral rays of the beam then pass through the anode plate obliquely, as may be seen in fig. 2, and are thus more attenuated than the rays along the axis; and, moreover, they must cover a greater distance to reach the skin. The result is a very non-uniform distribution of the intensity on the field irradiated, a phenomenon which meets strong objections from the doctor. The doctor, on the contrary, for the sake of easy and reliable dosage, requires the most uniform distribution possible.

In this laboratory an entirely different construction has been worked out, in which the own filter of the tube could be very much restricted [3]). The cathode is here earthed and the X-rays emitted by the anode pass through the opening in the ring-shaped anode.

In *fig. 3*, which shows a diagram of the end of the tube, this construction may be seen. The filament G, led through with one pole connected and the other insulated, is fastened in the earthed metal cathode can K. By means of the ring D the electrons emitted from the filament are focussed on the massive tungsten anode, which has a positive voltage of 50 kV with respect to the cathode. The X-rays excited on the anode pass out of the tube through a glass window behind the filament and fused into the cathode can. It is of importance here that practically cathode potential prevails over the whole space occupied by the window. There is thus no danger that secondary electrons freed on the anode will bombard the window, which therefore may be large and thin.

Surrounding the tube is an earthed metal jacket O, which is closed at the spot where the rays emerge by a thin cap of "Philite" in order to provide mechanical protection of the thin window. This cap can be placed directly against the skin surface to be treated, so that due to the very short distance between focus and skin a very steep depth gradient is obtained. The minimum distance between focus and skin amounts to 18 mm, while the X-rays need pass through no other filter than the glass window and the "Philite" cap; the combined filter

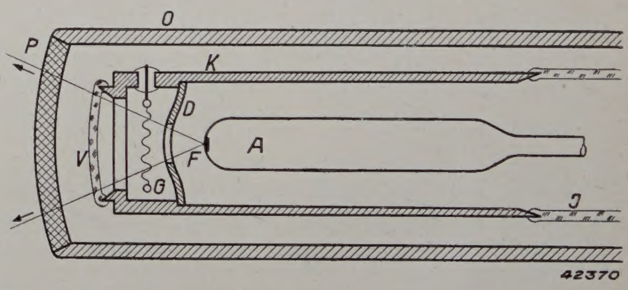

Fig. 3. Construction of the X-ray tube of the Philips *CT* apparatus for contact therapy. K earthed cathode can, G filament, D focussing ring, A anode, F focus, V window, I insulated connection between cathode can and anode holder, O jacket, P "Philite" cap.

effect of these is equivalent to 0.2 mm of aluminium. For the sake of comparison it may be mentioned that the own filter of other tubes for the same voltage is at least 1 mm of aluminium.

[3]) *Cf:* J. H. van der Tuuk and G. J. van der Plaats, Ned. T. Geneesk. **79**, 4025, 1935 and J. H. van der Tuuk, Ned. T. Natuurk. **3**, 129, 1936.

In *fig. 4* the variation of the intensity as a function of the depth beneath the skin is shown as measured [4]) upon irradiation with the tube described. It may be seen that, using the smallest possible distance (curve *1* for a distance of 2 cm), a very steep depth gradient is obtained: at a depth of 1 cm under the skin the intensity has already fallen to 22 percent of that on the surface.

It must be remarked that there is still some difference of opinion in medical circles as to what is practically the most suitable value for the depth gradient [5]). It will indeed depend more or less on the individual case. In some cases, therefore, a less steep gradient will be preferred. This can be obtained in a simple way by slightly increasing the distance from focus to skin or by introducing an extra filter for the rays. Curves *2* to *6* in fig. 4 show the different forms of intensity gradient under the skin which can be realized by these means. In the case of curve *6* (4 cm distance and filter of 2.7 mm of aluminium) the intensity at 1 cm depth still amounts to 49 percent of that on the surface.

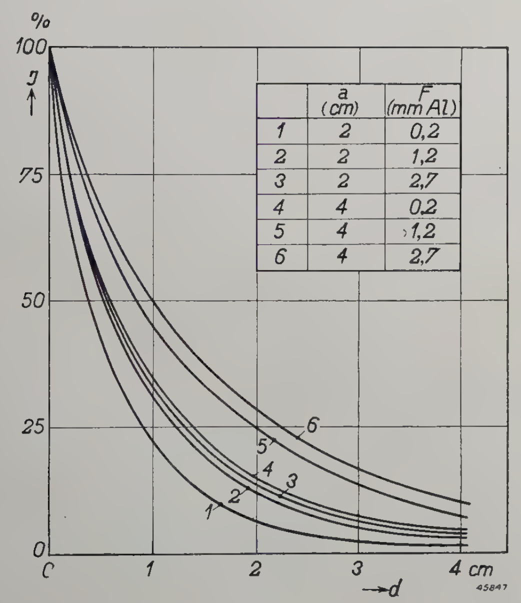

Fig. 4. Measured depth gradient of the tube of fig. 3 with 50 kV voltage. Intensity I in percent as a function of the depth d in cm.

The field distribution is very homogeneous with this tube, as is shown in *fig. 5*, where so-called isodose curves are drawn. These are lines connecting all points receiving the same dose. The field irradiated is here limited by a metal cap to a circle of 10 mm diameter. The dose over the whole skin surface exposed is practically uniform. At the same time the rapid decrease in the dose with depth and the sharp bounding at the sides may be seen from the figure. This bounding, also an important requirement of the doctor, is obtained by using a small focus. With a large focus only the

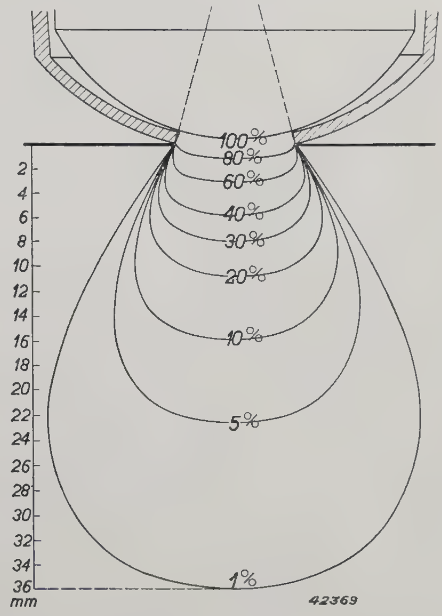

Fig. 5. Isodose curves obtained upon irradiation with the tube of fig. 3. The field irradiated on the skin is limited to a diameter of 10 mm by means of a metal cone with an opening.

field on the surface of the skin would be sharply limited by the metal cap, but the edge of the cap would cast a half-shadow, owing to which at some depth the lateral limitation of the field would no longer be sharp.

The jacket of the tube

In *fig. 6* a sketch is shown of a simplified cross section through the complete tube with jacket. (As may clearly be seen from the photographs of figs. *7*, *8* and *9* the tube is relatively still much thinner). The anode A on a long stem is supported by an anode holder H, which is insulated from the cathode K by a glass joint I. Between the tube and the earthed metal jacket O, which completely protects doctor and patient from the high voltage, a conical insulating tube of ebonite E is introduced. This made it possible to limit the diameter of the whole to about 50 mm (in the middle). The external diameter 2 r_2 of the ebonite tube near the anode holder is 48 mm, whilst the anode holder itself has a

[4]) *Cf.* for extensive results: G. J. van der Plaats, diss. Utrecht 1938. Compare too L. F. Lamerton, Brit. J. Rad. **13**, 136, 1940.

[5]) *Cf.* for example: W. Schäfer and E. Witte, Strahlentherapie **33**, 578, 1929; W. Chaoul and A. Adam, Strahlentherapie **48**, 31, 1933; G. J. van der Plaats, Theses, Utrecht, 1938; cf. also footnote 6); D. den Hoed, Acta Rad. **19**, 239, 1938 J. M. Woodburn-Morison, Medical World **12**, 231, 1933, P. A. Flood and D. W. Smithers, Brit. J. Rad. **12**, 462, 1939. Sven Hultberg, Acta Rad. **24**, 328, 1943.

diameter $2r_1 = 22$ mm and is at a voltage V of 50 kV. The greatest field strength in the ebonite (namely on the inner wall) is then [6])

$$E = \frac{V}{2.3\, r_1 \cdot \lg r_2/r_1} = 58 \text{ kV/cm}, \ldots \quad (2)$$

which is still far below the maximum permissible field strength in ebonite (150 kV/cm). Without the ebonite the diameter of the jacket would, as can be calculated with formula (2), have to amount to at least $2r_2 = 112$ mm, in order to limit the field strength on the anode holder to the maximum permissible value for air of 28 kV/cm.

During use a power of about 100 W is dissipated on the heated anode (tube voltage = 50 kV DC voltage, tube current = 2 mA). The anode gives off the heat developed by radiation to the cathode can. If this can had in turn to get rid of the heat by radiation towards the outside, it, and with it the whole extremity of the tube, would become much too hot, so that it would not be possible to place the tube directly against the surface of the skin or in a cavity of the body. It was therefore necessary to provide an intensive cooling. For the sake of simplicity in construction and ease in manipulation of the tube, air cooling was chosen. In the cabinet for the high-voltage generator a fan is mounted. A rubber tube surrounds the cable, which supplies the high voltage to the tube, and the fan blows air through the space between cable and rubber tube. As may be seen in fig. 6, the air flows between the tube and the ebonite insulation can, along the cathode can and back along the outside of the insulator can, to pass through holes in the ring to the outside. In this way the patient experiences no inconvenience from the current of air. The amount of air blown through the tube amounts to 2.4 liters per second. Since air has a heat capacity of 0.285 cal. per litre and per degree centigrade and the air passing through when the tube is in continuous use takes up 100 W sec = 24 cal, the temperature of the air rises 24/(2.4 × 0.285) = 35° above room temperature. The extremity of the tube does not therefore, become uncomfortably hot even after long use.

The method of cooling just described makes an air gap necessary between the anode holder and the ebonite insulator. Due to the fact that ebonite has a dielectric constant of 3, the field strength in this air gap is three times as high as in the adjacent ebonite [7]), thus a field strength which, according to the above mentioned values, is certainly many times greater than the breakdown strength in air. It may therefore appear remarkable that in this case no account is taken of the customary requirement that the breakdown field strength may not be exceeded at any point. Thanks to the presence of the ebonite no complete breakdown can occur; moreover, the ionized air is continually replaced by the cooling air current.

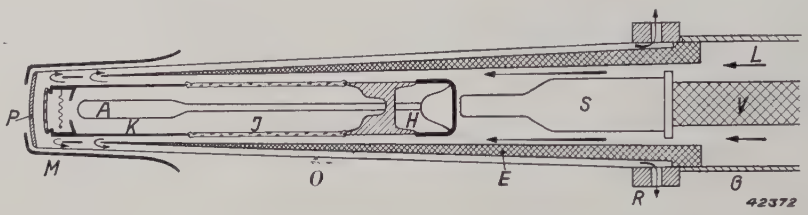

Fig. 6. Cross-section of the X-ray tube with jacket. From the photographs of figs. 7, 8 and 9 it may clearly be seen that the tube is actually very much thinner. K cathode can, A anode, H anode holder, I glass joint, O jacket with "Philite" cap P, E insulating tube of ebonite, V high-voltage cable, S plug, G rubber tube, L air inlet, R ring with holes for escape of air, M metal cone for accurate placing of tube on the skin.

Fig. 7. The tube in its jacket. The whole is 50 cm long and weighs 2.5 kg; it can easily be held in one hand by the handle.

Fig. 7 is a photograph of the tube in its jacket. The tube can easily be held with one hand, so that the treatment can also be by hand (*fig. 8*). This method has the advantage that during the

[6]) See for example: Philips techn. Rev. **6**, 270, 1941. We assume that we are here concerned with the case of two concentric cylinders with a homogeneous dielectric, and we shall later deal with more complex dielectrics.

[7]) See for instance the article cited in 6).

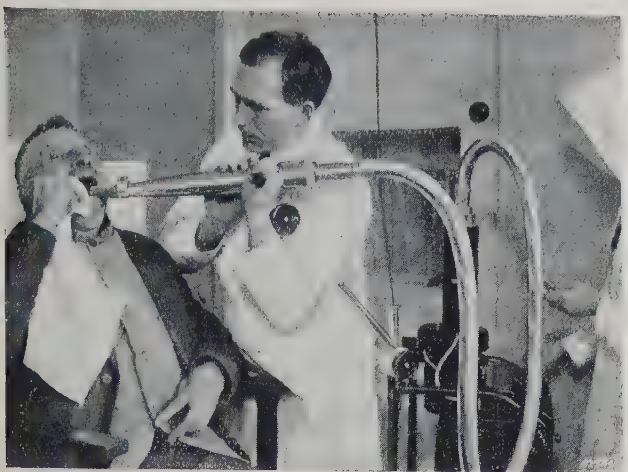

Fig. 8. The apparatus for contact therapy during treatment.

irradiation the tube follows the slight movements of the patient. The placing and adjusting of the tube is usually as follows; A metal cone (M in fig. 6) with an opening which is determined by the part to be irradiated is placed upon the spot to be treated. When the opening is exactly over the desired spot the doctor inserts the tube into the cone, which is held in position by the pressure of the tube, and the irradiation can be begun.

Instead of holding the tube in the hand it can also be mounted in a universally moveable arm fastened to the high-voltage generator, see *fig. 9*.

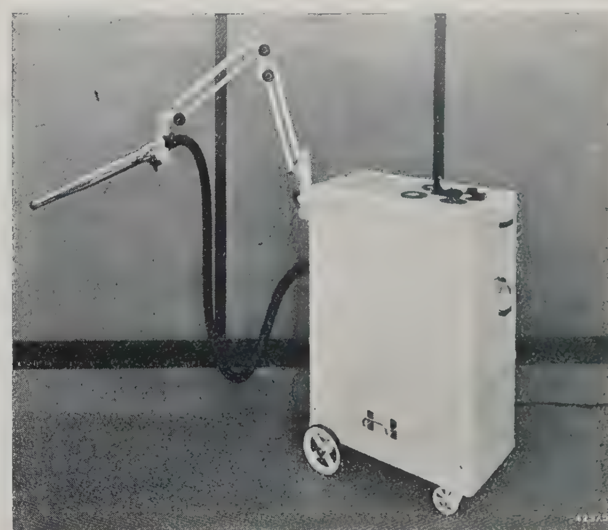

Fig. 9. The cabinet, containing the high-voltage generator and, above it, all the control and regulation elements, bears a universally moveable arm into which the X-ray tube can be fastened.

The tube supply

The tube is fed with direct current voltage, according to a scheme the principle of which is shown in *fig. 10*. It is desirable to use DC voltage especially because of the danger of flashover as a result of electron emission caused by the heating of the hot anode when the voltage across the tube is reversed [8]). By the rectification the function of opposing the high-voltage in the negative phase is now, as it were, passed on from the X-ray tube to the rectifier valve. The construction of the jacket with the glow discharges in the air gap might also be dangerous with AC voltage [9]).

For the avoidance of flashover a pulsating DC voltage would, in principle, also be sufficient, such as is obtained with the well known and often used Villard connections, see *fig. 11a*. As may be seen upon comparison with *fig. 11b*, in the Villard connections transformer, condenser and valve are subjected to only half as high voltages as in the case of a connection for slightly rippled DC voltage with the same peak voltage. The latter, however, offers the advantage that all the electrons attain the maximum velocity. With equal power, thus at a given capacity of the cooling, this is

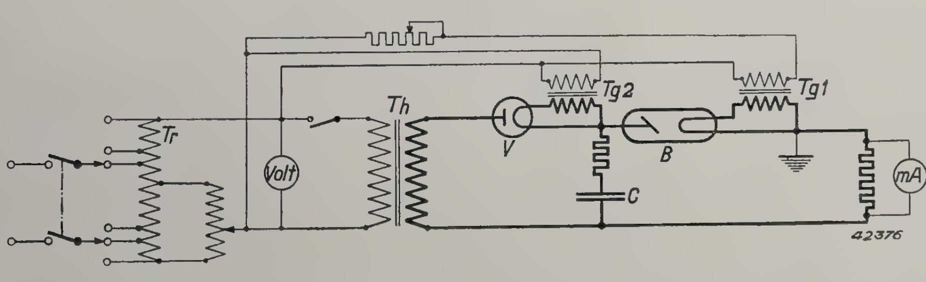

Fig. 10. Diagram showing the principle of the feeding of the tube. The high-voltage part is indicated by heavy lines. B X-ray tube, T_h high-voltage transformer, V rectifier valve, C tondenser, T_{g1} and T_{g2} filament current transformers, Tr. regulator transformer for correccion of mains voltage.

[8]) See: Philips techn. Rev. **6**, 309, 1941.

[9]) Compare the analogous situation in the case of gas-filled cavities in the dielectric of paper condensers: Philips techn. Rev. **4**, 254, 1939.

manifested directly in a shortening of the necessary times of irradiation. In addition there is also the fact that, thanks to the low power required and the relatively low voltage, the economy possible with the Villard connections is not of much importance here. The whole generator, which is housed in the cabinet shown in fig. 9, weighs only 20 kg.

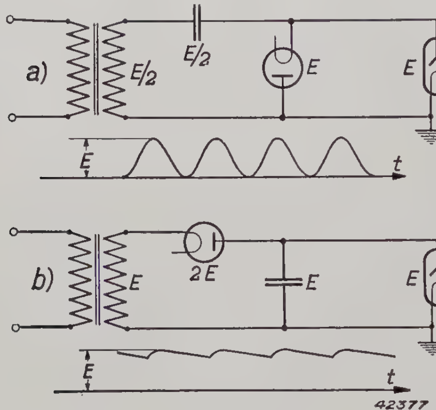

Fig. 11*a*) Villard connections.
b) Connections for obtaining much less strongly pulsating *DC* voltage, At the same peak value E of the voltage obtained, all the elements of the connections *a* can be constructed for a voltage only half as high as those of *b*.

Above the generator in the same cabinet are also housed all the switching and regulatory elements. Compared with various installations previously described, these include only one interesting feature which we shall discuss in some detail, namely an automatic regulation of the tube current. For satisfactory dosing it is necessary that the previously chosen tube current should be accurately maintained from the beginning to the end of a treatment. Now there are various circumstances which may have an unfavourable effect on the constancy of the tube current. In the first place there are always certain fluctuations of the mains voltage and consequently of the filament current of the tube. The electron emission depends so closely on the filament temperature that a mains voltage variation results in a ten percent greater variation of the tube current. This difficulty could be met by employing a stabilizer for the filament current, as is for example done in certain X-ray apparatus for diagnosis, where constant tube currents are likewise required[10]). In our case this method does not lead to the desired result because the relation between the filament current and the electron emission is not fixed to the same degree as in the apparatus for diagnosis mentioned above. This is due chiefly to the small distance between anode and filament: after switching on, the anode gradually heats up and heats the cathode by radiation, so that the emission increases even when the filament current is constant. The resulting increase in the tube current during the first few minutes after switching on is particularly unpleasant, since during the treatment, which should proceed smoothly and be finished within a few minutes (sometimes even within 10 sec.), instead of being able to devote his whole attention to the patient, the doctor would be compelled continually to regulate the tube current.

Now in order to eliminate all the causes of tube current variations simultaneously, a filament voltage regulator is employed which is governed by the tube current itself. *Fig. 12* shows the principle of the regulator. The filament current of the X-ray tube B is supplied by the transformer T_1, which in turn is fed by the transformer T_2 over the resistance R_1. In this resistance an extra voltage loss is caused by the current in the relay tube L. An increase in the average current through L will therefore cause a decrease in the average filament current. Now when we assume the potentiometer P to be in the position indicated by the dotted line, the voltage over the resistance R_3 acts on the grid of L. This voltage, which is smoothed by the condenser C_3, is proportional to the current through the X-ray tube. When the tube current increases the grid voltage of L becomes more positive, the moment of ignition of this tube in each period of

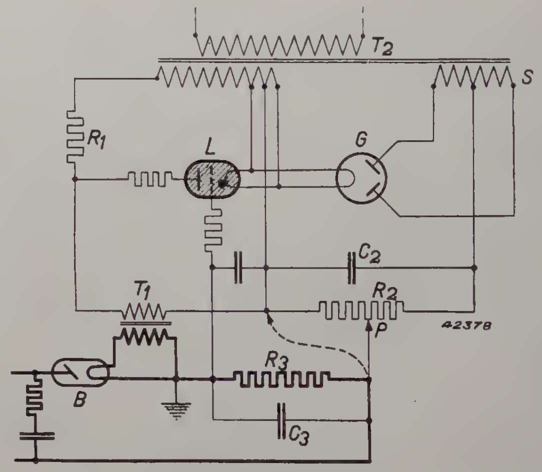

Fig. 12. Simplified scheme of the regulator for automatically keeping the tube current constant. See the description in the text of the article.

the AC voltage supplied by T_2 is advanced, the average current through the relay tube rises and the result is a fall in the filament current of the X-ray tube, so that the increase of the tube current is compensated. The regulatory mechanism thus tends to maintain the nominal tube current.

[10]) Philips techn. Rev. 6, 12, 1941.

The nominal tube current can be determined with the potentiometer P. With this potentiometer a variable part of the fixed DC voltage over R_2 (obtained by rectification of the AC voltage acting on S by the rectifier valve G and smoothing by C_2) can be subtracted from the bias on R_3C_3. The grid of the relay tube then becomes less positive with the same tube current and the mechanism only reaches on equilibrium at a higher tube current.

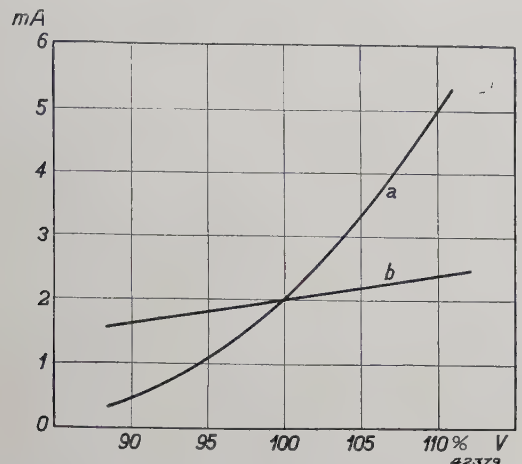

Fig. 13. Change of the tube current in mA upon fluctuations of the mains voltage expressed in percent. Curve *a* without regulator, curve *b* with regulator.

The effect of the regulatory arrangement can be seen in *fig. 13*, where the tube current is drawn as a function of the mains voltage. Without regulator the current set at 2 mA varies between 0.55 and 5 mA with approximately 10 percent variation of the mains voltage, *i.e.* between 28 percent and 250 percent of the nominal value; with the regulator the current remains between 1.6 and 2.4 mA, *i.e.* between 80 and 120 percent of the nominal value. The decrease in the effect upon heating-up is not made evident in this graph, but experiments have shown that this effect is practically inappreciable with the current regulator.

Practical application of the apparatus

We have already pointed out that due to the small distance between focus and skin very high radiation intensities can be obtained. With 50 kV tube voltage and 2 mA tube current the intensity at the surface of the "Philite" cap amounts to not less than 7000-8000 röntgen per minute. For the sake of comparison it may be mentioned that in fluorscopy of the lungs of a patient receives a dose of abour 2 *r*, that the dose necessary to cause an erytheme amounts to about 600 *r*, while 0.2 *r* is the tolerance dose, *i.e.* the dose which the operator of X-ray installations may receive daily without harm in the long run. For the therapeutic treatment of tumours of the skin total doses of, for instance, 3000 to 20,000 *r* are required. Thus a total time of irradiation of not more than several minutes is usually sufficient. This makes it possible, if desired, to "burn out" the tumour in one treatment (so-called X-ray caustic of van der Plaats). But also when for certain reasons it is not desirable to administer the total dose in a single treatment, it is in any case possible to treat the patient without hospitalization. This is in contrast to a radium treatment where the normal radiation intensity is about a thousand times smaller, so that the irradiation occupies several days. This great advantage has already contributed to the application of X-ray treatment to a much larger circle of patients. It does not, however, mean that radium treatment can be replaced by contact therapy in all cases. The choice between the two methods of treatment will often be decided by the doctor according to the ease of application in a given case.

At the beginning we showed that surface therapy, and especially contact therapy, is in a much more favourable position than depth therapy. The percentage of cures with contact therapy is very high, and in cases where there is a free choice between the two methods, namely in the case of tumours in cavities of the body, preference will usually be given to contact therapy. It is perhaps possible that in a not too distant future methods will be developed to make more deeply lying tumours accessible for the method of contact therapy with the help of operational technique.

THE MEASUREMENT OF IMPEDANCES PARTICULARLY ON DECIMETRE WAVES

by J. M. van HOFWEEGEN.

621.317.33.029.63

Several methods are discussed by which impedances can be measured at radio frequencies. At wave lengths above 1 metre it is customary to connect the impedance to be measured in parallel with an oscillation circuit and to calculate the required impedance from the detuning and damping influence experienced by the circuit. On decimetre waves a Lecher system is used as oscillation circuit. This article describes the manner in which this method has been worked out in the Philips Laboratory. As measuring instrument for the high-frequency voltage a diode voltmeter needing only relative calibration is used.

Introduction

With the increasing use of high frequencies in radio technology and television, namely waves of from several metres to a few decimetres, the necessity is more and more felt of having at one's disposal methods of measuring the impedances present at such frequencies. As one important field of application for such methods of measurement we may, for example, mention the measurement of the input and output impedances of amplifier valves, which impedances are very important for the use of those valves. A second important application is the measurement of the impedance of leakage resistances; at high frequencies the impedance of such resistances may deviate considerably from the D.C. resistance, due to skin effect and parasitic capacities and self-inductions. For use in a circuit a knowledge of the correct resistance value at the frequencies used is very important.

The characterization of impedance

The importance of a circuit or of an element in a circuit may be characterized in different ways; the simplest way is by the determination of the absolute value of the ratio between terminal voltage and terminal current and of the phase shift between these two quantities. Another manner, which often offers advantages for obtaining a clear insight, and which is therefore very commonly used in high-frequency technique, is the indication of an equivalent parallel or series connection of two elements, one of which is a pure resistance and the other a loss-free reactance. Thus for example the input impedance of a radio valve is often indicated by an equivalent connection in parallel of a resistance and a capacity, the resistance in particular depending closely upon the frequency. In measuring an impedance in high-frequency technique it generally suffices, in fact, to determine the two elements of this parallel connection.

Before discussing the measurement of impedances on decimetre waves, we shall first deal with the methods of measurement which are customary in the case of long waves.

Measurements of impedance at wave lengths greater than about 1 metre

The methods by which it is customary to measure an impedance at low frequencies (from current

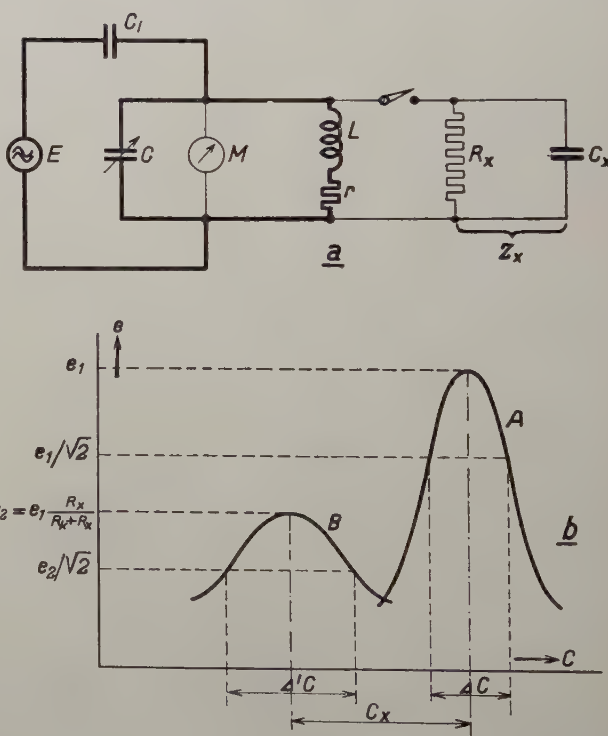

Fig. 1*a*) Diagram showing the principle of the method by which impedances can be determined at wave lengths above 1 metre. E is a source of high-frequency voltage. The coil L with resistance r and the calibrated variable condenser C form an oscillation circuit. M is a measuring instrument for determining the high-frequency voltage on this circuit. R_x and C_x characterize the impedance Z_x to be measured.
b) The high-frequency voltage e_m read off on M as a function of the capacity C. A without Z_x; B with Z_x.

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[1]) See for instance Philips techn. Rev. 3, 357, 1940

and voltage with a Wheatstone bridge or more complicated bridge connections), cannot be used at radio frequencies without very special precautions. The chief reason for this is that due to the inevitable parasitic capacities and self-inductions in the connections it is never entirely certain whether the same current flows in two components connected in series, while also the presence of the same voltage between the terminals of two components connected in parallel is by any means not always assured. It is therefore customary to measure an impedance at high frequencies from the detuning and damping effect which that impedance exerts on an oscillation circuit. The principle of the connections used to do this is represented in *fig. 1a.* The oscillation circuit consists of a coil with the self-induction L and the resistance r and in parallel to it a calibrated variable condenser C. The circuit is coupled with the source of high-frequency voltage e, for example *via* a condenser C_k, while the voltage measuring instrument M, to which we shall revert later, is connected in parallel with the circuit. At the same time the impedance Z_x to be measured, which is for instance characterized by R_x and C_x, can be connected in parallel with the circuit.

The measurement is now performed as follows. The circuit (without Z_x) is first tuned to the frequency of the source of high-frequency voltage. The voltage read off on M, e_1 (see fig. 1b) is then a maximum. The condenser C is then increased and reduced, in both cases in such a way that the voltage on the circuit becomes smaller by a factor $\sqrt{2}$ with respect to e_1 [3]). If the difference in capacity read off on C in both these cases is equal to ΔC, the following relation exists between ΔC and the resonance resistance R_k of the circuit:

$$R_k = \frac{2}{\omega \Delta C}, \quad \ldots \ldots \quad (1)$$

where ω is the angular frequency of the high-frequency voltage applied to the circuit.

The impedance to be measured is then connected in parallel with the circuit. The condenser C must then be reduced in order to bring the circuit into tuning again. The amount by which C must be reduced is equal to C_x [4]). After the connection of Z_x and the retuning of the circuit, the voltage on the circuit e_2 is smaller than it was when the circuit was tuned to the measuring frequency without Z_x, since the resonance resistance now consists of the connection in parallel of R_k and R_x. By means of a simple calculation it can be shown that e_1 and e_2 are in the same ratio as the resonance resistances, thus:

$$e_1 : e_2 = R_k : \frac{R_k\ R_x}{R_k + R_x},$$

or

$$\frac{e_1}{e_2} = \frac{R_k + R_x}{R_x} \quad \ldots \ldots \quad (2)$$

R_x can now be calculated from (1) and (2).

The following is a variation of this method of measurement. After the connection of Z_x and the retuning of the circuit, C is again increased and reduced, this time by such an amount that the voltage on the circuit with respect to e_2 becomes smaller by a factor $\sqrt{2}$. If a total variation of capacity $\Delta' C$ is necessary for this (see fig. 1*b*), the connection in parallel of R_k and R_x is given by the relation

$$\frac{R_k R_x}{R_k + R_x} = \frac{2}{\omega \Delta' C}. \quad \ldots \quad (3)$$

It finally follows from (1) and (3) that

$$R_x = \frac{2}{\omega\,(\Delta' C - \Delta C)}, \quad \ldots \quad (4)$$

The first method described here, the one in which the resonance resistance after the connection of Z_x is found from the height of the peak of the resonance curve, is especially suitable for measuring impedances where the resistance component R_x is larger than the circuit resonance resistance R_k. Due to the connection of Z_x and the retuning of the circuit, the resonance resistance of the whole then undergoes only a relatively small change and e_2 is not much smaller than e_1. The high-frequency voltage supplied by the source of voltage can now be chosen so high that this small variation in voltage can be read off with a wide deviation of the voltmeter M. If the second method is applied, where the resonance resistance after the connection of Z_x is determined by the detuning of the circuit, then according to (4) the change must be measured which is experienced by ΔC through the connection of Z_x. Since ΔC is quite small as a rule, a small variation in its value can only be determined with less accuracy.

If on the other hand R_x is so small compared with R_k that e_2 is considerably smaller than e_1,

[2]) The capacity of the circuit is then formed by $C + C_i$.

[3]) A different factor can also be chosen. The formula for R_k, however, does not then assume the simple form represented by (1).

[4]) When the impedance to be measured may be represented by a connection in parallel of a resistance R_x and a self-induction L_x, C must be increased by an amount $\frac{1}{\omega^2 L_x}$.

the last-mentioned method is to be recommended. Since by this method it is not necessary to compare e_2 with e_1, by increasing the voltage supplied by the source of voltage provision can be made for reading off e_2 also at a wide swing of the measuring instrument M. Since in this case the difference between ΔC and $\Delta' C$ will be fairly large, the objection to this method raised in the preceding paragraph is met.

Since, as mentioned above, it is often necessary to be able to read off accurately very small values of ΔC or $\Delta' C$, while a rather large variation of C is often necessary for the measurement of C_x, in practice, instead of a single variable condenser, a connection in parallel of two calibrated variable condensers is generally used, namely a small one for the determination of ΔC and if necessary $\Delta' C$, and a large one for measuring C_x. It must further be pointed out that the absolute value of the circuit capacity is of no importance for the measurement, so that the capacity of wiring and the like plays no part. For this reason also it is not necessary to make C_k especially small. C_k may be considered as forming a part of the total circuit capacity. A large value of C_k will therefore not influence the accuracy of the measurement in the first instance. It must, however, be taken into account that with a large value of C_k the circuit is often strongly damped by the internal resistance of the voltage source. The result of this is a small value of R_k, which makes the determination of a large R_x inaccurate.

The method of measurement described is only possible due to the fact that a good variable condenser is practically loss-free at the frequencies in question, so that a variation of C does not affect the losses of the circuit. The use of a variable condenser which cannot be considered loss-free leads to incorrect results.

According to the principle described here impedances can be measured where the resistance compontent R_x is of the same order of magnitude as the resonance resistance of the oscillation circuit used (for instance from 20 R_k to 1/20 R_k).

When it is desired to measure a very small impedance, such as for example the impedance of a short metal wire, an oscillation circuit must thus be constructed with a very small resonance resistance. This would necessitate the use of a very large variable condenser (the resonance resistance is given by L/rC). Since in addition to the requirements of accuracy and freedom from losses this condenser is also bound to maximum dimensions (see later) especially at wave lengths below 10 meters, a lower limit is thereby set to the value of R_x which can be measured by this method. Very small impedances can, however, be measured by a similar method. They are then not connected in parallel with the oscillation circuit, but in series with the circuit coil. The formulae to be applied in this case are less simple than those given above. In order to work them out a knowledge is required of the absolute value of the capacity C (or of the self-induction L).

In practice the method described can be applied for wave lengths of up to 1 metre, not already at wave lengths of several meters certain precautions are necessary in order to avoid systematic errors in measurement. Special attention should be paid to keeping the connections between the various components very short in order to prevent the self-induction of the connecting wires from causing incorrect results. Where for mechanical reasons a connection cannot be made short enough, it may be necessary to compensate the self-induction of the connecting wire by connecting a capacity in series with the wire in question. Thus in *fig. 2*

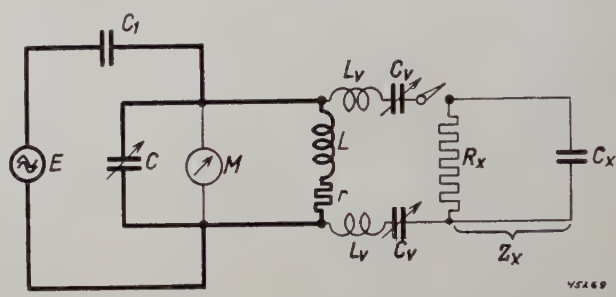

Fig. 2. The self-inductions L_v of the connecting wires of the impedance to be measured can be compensated by capacities C_v. See the text under fig. 1 for the meaning of the other symbols.

it is indicated how the self-induction L_v of the connections between the impedance to be measured and the circuit can be compensated by capacities C_v, which are in series resonance with L_v [5]), so that the following holds: $\omega L_v = 1/\omega C_v$.

Another objection which often arises is that the calibration of the condenser C, which has usually been carried out at a low frequency, is no longer correct at the high frequency at which the measurement is made, owing to the self-induction of the connecting wires. In these connections also, therefore, capacities should be included in this case. Furthermore the dimensions of the condenser C should be kept small, since otherwise the self-induction of the fixed and rotating plates may cause the above-mentioned difficulty. Since in this case the self-induction depends upon the size of C, it cannot be eliminated by a condenser in the connections.

[5]) The adjustment of these capacities to the correct value may take place in different ways. A common method is to connect a second voltage measuring instrument instead of Z_x and to adjust the condensers C_v in such a way that the voltage which is read off on the latter instrument is equal to the voltage read off on M.

Not only is it possible to determine the resonance resistance of an oscillation circuit from a variation in capacity, but it is also possible by a variation in the frequency of the high-frequency voltage source. A fixed tuning capacity can thus be used in this case. The frequency is now varied so much that the circuit voltage is decreased by a factor $\sqrt{2}$ on both sides of the resonance peak. When the total frequency variation necessary for this is Δf the resonance resistance is given by

$$R_k = \frac{1}{2\pi C \Delta f} \quad \ldots \ldots \ldots \quad (5)$$

Since at the very high frequencies as considered here the accurate measurement of small frequency variations is generally more difficult than the accurate calibration of a variable condenser, the measurement of a fixed frequency and a variable capacity is of more importance in practice.

Practically the only measuring instrument which can be used for the measurements in question is a diode voltmeter. In order to keep the connections, which carry the high-frequency AC, short, the diode is generally soldered directly to the circuit. In *fig. 3* a diagram is given of the way in which a diode voltmeter can be connected. *Via* a condenser C_d the diode D is joined with the top of the oscillation circuit. The DC voltage obtained on the diode causes a direct current in the leakage resistance R_1 which is measured with the micro-ammeter M_1. The battery V_a and the potentiometer R_a make it possible to give a small negative voltage to the anode of the diode, so that the operating point can be adjusted to a favourable position on the diode characteristic. The battery V_f and the variable resistance R_f serve for the provision and regulation of the heating current for the diode.

Further it must be noted that the diode voltmeter needs only to be calibrated relatively for these measurements. Since it is only desired to measure voltage relations, the absolute value of the high-frequency voltage is of no importance. It is also unnecessary that the same high frequency voltage should act on the diode as on the oscillation circuit. The coupling between the two may therefore, if desired, be very loose, with a small value of C_d. If necessary the diode can also be coupled with the oscillation circuit in some other way, for example through an inductive coupling with the coil L.

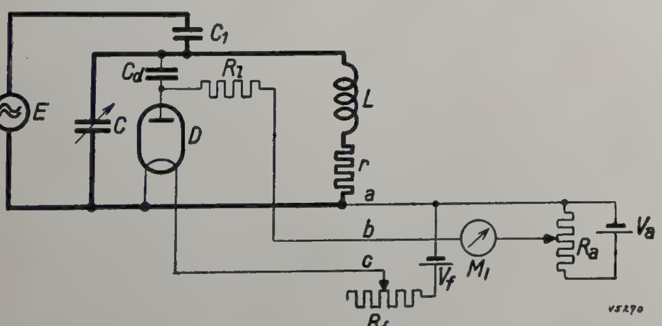

Fig. 3. Connections of the diode voltmeter for measuring the high-frequency voltage on the oscillation circuit. D is the diode, R_l the leakage resistance, M_1 is a microammeter, V_f and V_a are batteries for supplying the filament current and a small negative anode voltage which can be regulated, respectively, with the variable resistance R_f and the potentiometer R_a. The connections indicated by a, b and c do not carry H.F. current, and may therefore have any length.

As a rule the calibration of the diode voltmeter is carried out at a low frequency. Now there are two reasons why a calibration performed at a low frequency is no longer correct at very high frequencies. The first lies in the self-induction of the supply lines to the diode and the capacity of the diode. This, however, affects only the absolute calibration [4]). The second reason results from the fact that the electrons need a certain time to reach the anode from the cathode; although this time is very short, often at very high frequencies it may not be neglected, having regard to the oscillation time of the anode AC voltage. Since the transit time of the electrons depends upon the anode voltage, the frequency at which the influence of the transit time of the electrons on the calibration of the diode voltmeter begins to be felt, will be in part determined by the magnitude of the AC voltage applied to the diode. The result is that at very high frequencies there is also an effect of the frequency on the relative calibration. In order to keep the transit time of the electrons very short and thereby to make the calibration performed at a low frequency still valid at the highest possible frequency, for measuring purposes diodes are used which have been especially developed for this purpose [6]), whereby among other features, especial attention has been paid to procuring a small distance between anode and cathode.

Impedance measurements on decimetre waves

For wave lengths below 1 metre it is practically impossible to make a normal oscillation circuit with variable capacity, since the self-induction and capacity necessary are too small. It is, however, possible to construct a cavity resonator for wave lengths below 1 metre, but there are various objections to this for measurements by the method described above. The chief of these objections

[6]) See Philips techn. Rev. 7, 124, 1942.

is that the connection of the impedance to be measured would have to be inside the cavity resonator in order to keep the connections short, and a very impractical construction would result.

An obvious solution would of course be to use a Lecher system and self-induction. In the following we shall describe a method of measurement worked out in this laboratory in which use is made of a Lecher system.

A Lecher system which is short-circuited at one end and the length of which is about equal to a quarter wave length, shows much similarity to an oscilation circuit with concentrated capacity and self-induction in which the two are connected in parallel (parallel circuit). Similarly to the latter, the Lecher system exhibits a high resonance resistance [7]) with sufficient freedom from loss. Detuning of the system may take place by changing the length, thus by shifting a movable short-circuiting bridge. We can now determine the resonance resistance in a way which is entirely

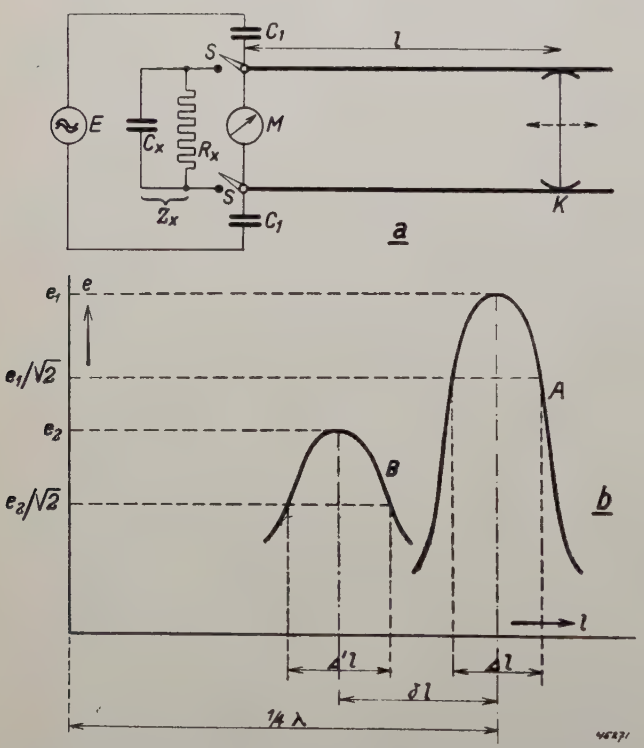

Fig. 4*a*) Diagram showing the principle of the method by which impedances can be measured with the help of a tuned Lecher system. The system, of which the length is l, is coupled by means of the small capacities C_k with the source of high-frequency voltage E. M is a measuring instrument for indicating the high-frequency voltage on the input terminals of the Lecher system. R_x and C_x characterize the impedance to be measured Z_x. K is the movable short-circuiting bridge with which the Lecher system is tuned.

b) The high-frequency voltage e read off on M as a function of the length l. A without Z_x; B with Z_x.

[7]) See Philips techn. Rev. 6, 240, 1941.

analogous to the method followed in a parallel circuit. For this purpose the Lecher system is coupled with a high-frequency voltage source e, for instance by means of small capacities C_k (*fig. 4a*; the switches S are for the time being assumed to be open). The high-frequency voltage at the terminals of the Lecher system can be read off on a measuring instrument M.

The resonance resistance is now measured as follows: The Lecher system (without Z_x) is first tuned to the frequency of the source of high-frequency voltage e. The voltage e_1 (see fig. 4*b*) read off on M is then a maximum. The length is then increased and decreased, in both cases in such a way that the voltage with respect to the maximum becomes smaller in the ratio $1:\sqrt{2}$. If the distance between these two positions of the short-circuiting bridge is Δl the following relation holds between the resonance resistance R_x and Δl:

$$\frac{R_s}{\zeta} = \frac{\lambda}{\pi \Delta l} = \frac{6 \cdot 10^{10}}{\omega \Delta l}, \quad \quad (6)$$

where ζ represents the wave resistance [7]) and Δl is expressed in cm. This formula only holds as long as Δl is small compared with a quarter wave length. A normal system, however, always exhibits such a high resonance resistance R_s that Δl is small enough to permit the application of formula (6).

Formula (6) shows much similarity with (1) and this similarity can be made plainer by a slightly different form of the equation. If we call the self-induction and the capacity of the Lecher system per unit of length L^I and C^I, respectively, the wave resistance[5]) is given by

$$\zeta = \sqrt{\frac{L^I}{C^I}},$$

while there is the following relation between L^I and C^I:

$$\sqrt{L^I \cdot C^I} = \frac{1}{v} = \frac{2\pi}{\omega\lambda},$$

where v represents the velocity of propagation of the electromagnetic waves along the Lecher system.

When we obtain for the resonance:

$$R_s = \frac{2}{\omega C^I \Delta l}.$$

Since C^I represents the capacity per unit of length $C^I \Delta l$ is the variation in capacity of the system and thus the expression corresponds exactly to (1).

In the foregoing it was assumed that the Lecher system is in resonance with the voltage of the measuring transmitter at the length l, which is exactly equal to a quarter wave length (see fig. 4*b*, curve A). In practice, however, this cannot usually be realized. It is impossible to avoid the occurrence of a certain capacity between the connection terminals, *i.e.* the capacity of the

insulator by which the extremities of the two conductors must be supported and the capacity of the coupling condensers C_k. Due to these capacities resonance will occur with the transmitter voltage at a length l which is shorter than a quarter wave length. When the capacity in question can be kept so small that the length l at which resonance occurs differs only slightly from a quarter wave length, formula (6) can also be used for the calculation of the resonance resistance. If, however, the capacity in question is not small enough for that, a compensation of that capacity can be obtained by means of an auxiliary Lecher system (see later).

For the measurement of Z_x, this impedance is now connected in parallel with the Lecher system (fig. 4*a*, the switches S being closed). If the impedance to be measured may be characterized by the connection in parallel of a resistance and a capacity, the length of the Lecher system must be decreased in order to bring the system into tuning again with the high-frequency voltage applied. If the length by which l must be decreased is equal to δl (see fig. 4*b*), C_x is determined by

$$\omega C_x = \frac{1}{\zeta} \tan 2\pi \frac{\delta l}{\lambda} \quad . \; . \; . \; . \; . \; . \quad (7)$$

If the impedance to be measured can be represented by a connection in parallel of a resistance and a self-induction L_x, for retuning l must be increased. The self-induction L_x can then be calculated from the equation

$$\omega L_x = \zeta \operatorname{cotan} 2\pi \frac{\delta l}{\lambda} \quad . \; . \; . \; . \; . \; . \quad (8)$$

For the determination of the resonance resistance of the Lecher system and of the reactive part of the required impedance, therefore, the Lecher system is used in the same way as the parallel circuit already discussed, although with the application of somewhat different formulae. In the determination of R_x, however, account must be taken of the fact that in a Lecher system the losses are dependent on the variable element, namely the length, in contrast to the losses of the parallel circuit, which do not depend upon the variable element (loss-free condenser). While in the connections according to fig. 1*a* the inclusion of a loss-free condenser C_x (thus without R_x) and the corresponding decrease of C exert no influence on the resonance resistance, in the connection according to fig. 4*a* the resonance resistance *does* experience an alteration due to the connection of a loss-free condenser C_k and the corresponding decrease of l. It would, therefore, lead to incorrect results if one reckoned that after the connection of Z_x and the retuning of the Lecher system the resistance between the terminals would be composed of the connection in parallel of R_x and the value of R_s calculated from (6). The determination of R_x from the ratio of e_2 to e_1 or from $\Delta' l$ and Δl (see fig. 4*b*) is now also possible, but this calculation leads in general to unreliable results, since the manner in which the losses depend upon the length of the Lecher system is usually not known accurately. These losses are due to various causes, namely:

a) the resistance of the conductors and of the moveable short-circuiting bridge,
b) the resistance of the contacts between the conductors and the short-circuiting bridge,
c) losses in the insulators by which the conductors must be supported,
d) radiation of the conductors and of the short-circuiting bridge.

It now depends upon the construction of the system what relation these losses will have to each other. In the case of a Lecher system used without shielding the radiation of the short-circuiting bridge is often dominant. By the introduction of suitable shielding the radiation losses of conductors and short-circuiting bridge can be eliminated for the greater part, but this can never be complete in the case of the first-mentioned, since the shielding must be open at the side where the impedance Z_x is to be connected, and the parts of the conductors lying in the vicinity of this opening will thus radiate.

Each of the losses mentioned exhibits a different kind of dependence on the length of the Lecher system. In practice this is found to be of no importance to the application of formula (6) which relates only to small variations in the length, in the neighbourhood of 1/4 wave length. The losses of the Lecher system, even at large values of δl, have in the first approximation no influence on formulae (7) and (8). The quantities e_2 and $\Delta' l$ are, however, dependent on the way in which the losses are connected with the length of the system. It is thus in general impossible to calculate R_x in a simple way from the ratio between e_1 and e_2 or from Δl and $\Delta' l$. Only when the impedance to be measured possesses practically no reactive component, thus when δl is small compared to a quarter wave length, can R_x be determined by one of these methods.

In many cases the main cause of the losses occurring does not lie in the Lecher system proper, but in the measuring instrument M. The losses are then entirely concentrated at the connection terminals of the system. In that case the determination of R_x may take place by one of the above mentioned methods, even with a larger value of δl. In the determination from Δl and $\Delta' l$ the connection in parallel of R_x and R_s is given by the formula:

$$\frac{R_x\ R_s}{R_x + R_s} = \frac{\lambda}{\pi \Delta' l} \cos^2 \left(2\pi \frac{\delta l}{\lambda}\right)$$

which equation in combination with (6) makes possible the calculation of R_x.

Owing to the uncertainty mentioned about the way in which the losses depend upon the length of the Lecher system, it is desirable to construct the measuring arrangement in such a way that the measurement of R_x may take place while the length l is the same as that at which R_s was measured. A practical method is to connect a second Lecher system (*fig. 5*) with the initial terminals of the above mentioned Lecher system. This second system is likewise provided with a moveable short-circuiting bridge so that its length l_{II} can also be adjusted.

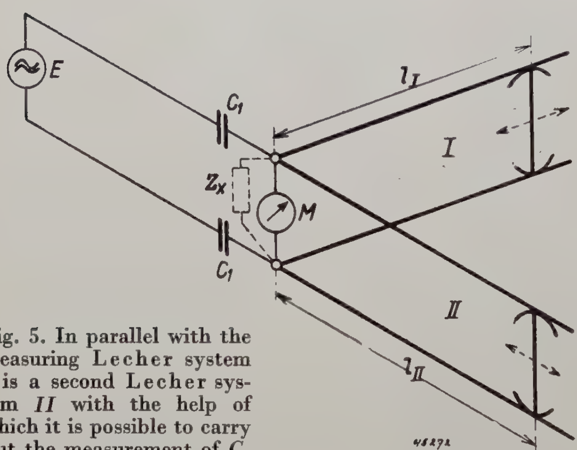

Fig. 5. In parallel with the measuring Lecher system I is a second Lecher system II with the help of which it is possible to carry out the measurement of C_x as well as of R_x, while the length l_I deviates only slightly from a quarter wave length.

Let us now first assume that l_{II} is equal to a quarter wave length. The input impedance then has no reactive component from this. As a result the measurement of C_x may take place with the aid of system I, entirely as described above. Now if the system II is exactly like system I, the measurement of R_x can be performed with the help of II. For practical reasons, however, in the installation constructed in this laboratory, system II is built differently from system I (see below). In order to determine R_x one now sets to work as follows.

After C_x has been determined with the help of system, I l_I is again set at a quarter wave length. The length l_{II} is now changed so that C_x is compensated by the reactive component of the input impedance of system II, which is ascertained from the fact that the deviation of the measuring instrument M is then at a maximum. The impedance between the terminals of the two Lecher systems is now composed of the connection in parallel of R_x, R_s and the input resistance of system II which we shall indicate by R'_s. The magnitude of this parallel connection can now be determined with system I by measuring $\Delta' l$ (δl now being equal to zero), and we can calculate R_x from this if we know the parallel connection of R_s and R'_s. Since R'_s depends upon the length l_{II} of the auxiliary Lecher system, the latter parallel connection must be measured at that length of l_{II} at which system II is in resonance with C_x. This can be done most simply by connecting with the terminals, instead of Z_x, a loss-free condenser the size of which corresponds to C_x. Since at the wave length considered here it will seldom be necessary to measure capacities of more than a few pF, this auxiliary capacity may take the form of two small metal plates a short distance apart. The adjustment of the capacity then takes place by bending these plates.

The auxiliary Lecher system has still another function in the measurement. The diode voltmeter is inductively coupled with the short-circuited end of the system. Since here also a relative measurement of the high frequence voltage is sufficient, it is unnecessary to know the absolute value of the voltage at the terminals of system I. It is thus sufficient to measure the voltage between the terminals m and n of a loop which is inductively coupled with the short-circuited end of Lecher system II (See *fig. 6*). At any length l_{II} this voltage is proportional to the terminals voltage of the two systems. By applying this possibility of setting up the diode at some distance from the terminals of the Lecher system, various structural objections are met which occur in the connection of a diode directly to these terminals. In particular it is generally very difficult to keep the connections to the impedance to be measured short when a diode is introduced at this spot. The inductive coupling of the voltmeter with the short-circuiting bridge of system II makes it impossible to consider this system as being actually short-circuited. For this reason it is desirable that the measurement not only of C_x, but also of R_x, should be carried out with the help of system I as described above.

As has already been indicated, there is always

a certain capacity between the connection terminals, owing to which it would not be possible to use a length l_I which is approximately a quarter wave length. In the variable length l_{II} of system *II* one has a means of compensating these capacities, so that all the measurements can therefore be carried out at a length l_I of Lecher system *I* which differs only little from a quarter wave length.

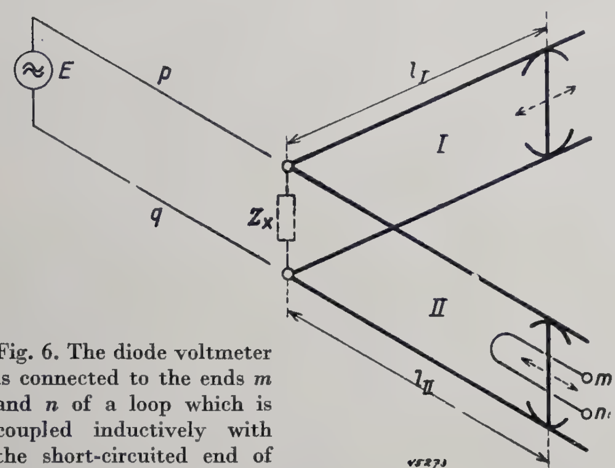

Fig. 6. The diode voltmeter is connected to the ends *m* and *n* of a loop which is coupled inductively with the short-circuited end of system *II*. The coupling with the measuring transmitter *E* is realized by the situation of the ends of the two conductors *p* and *q* at a short distance from the connection terminals of the Lecher system.

The coupling of the source of voltage (measuring transmitter) *E* with the measuring arrangements can be carried out by placing the ends of the two conductors *p* and *q* at a short distance from the connection terminals of the two Lecher systems (see fig. 6). By a variation of this distance the coupling can be regulated according to need. In order to keep the connections short the impedance to be measured is not, as is represented in fig. 4*a* for the sake of simplicity, connected by means of switches, but the object to be measured is soldered directly to the terminals.

Fig. 7 is a sketch of a measuring set-up as described in the foregoing. The arrangement shown here is used for impedance measurements at wave lengths of about 50 cm.

Just as in measurements with a parallel circuit, in those with a Lecher system there is a lower limit to the resistance R_x which can be measured[8]). At a small value of R_x according to formula (6) a large value of Δl is necessary, and for a value of

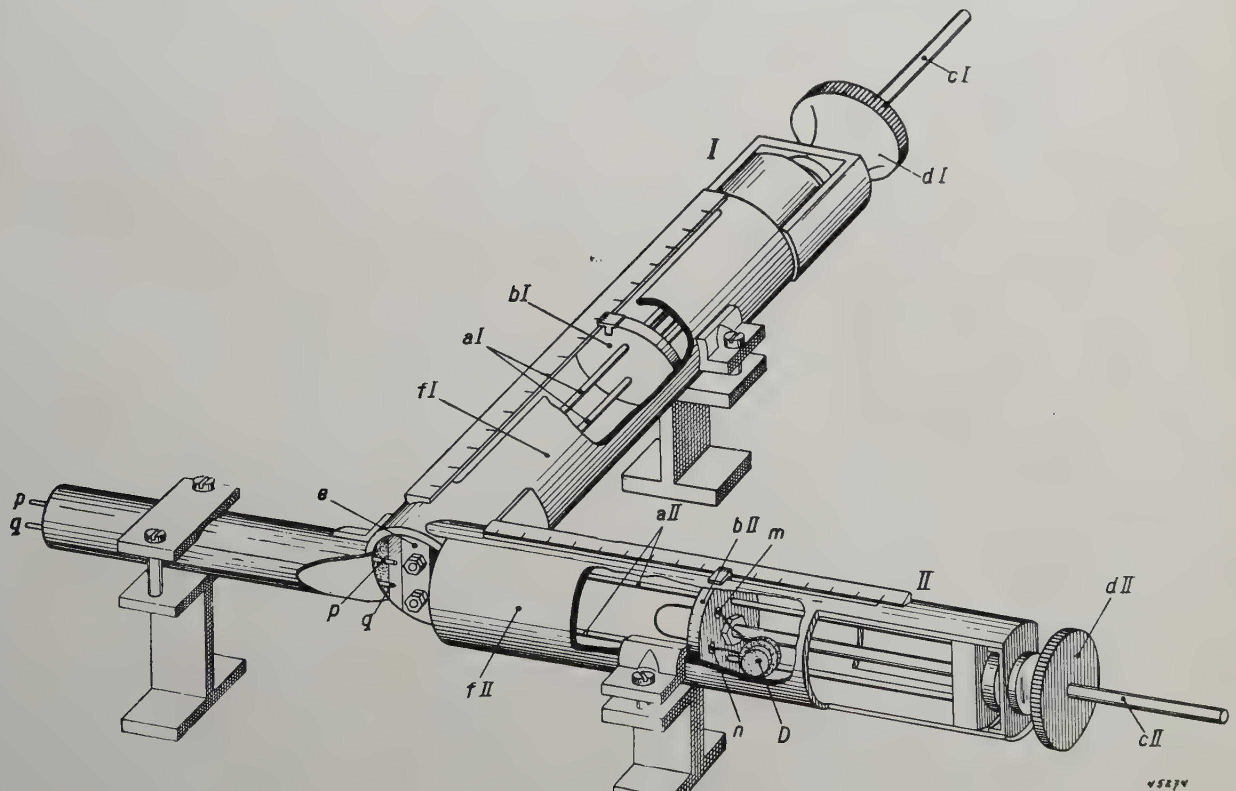

Fig. 7. Sketch of an arrangement for the measurement of impedances at wave lengths of about 50 cm according to the principle indicated in fig. 6. In order to show the construction clearly the shields *f* which surround the Lecher systems are partially cut open. For the meaning of the symbols *I, II, p, q, m* and *n* we refer to figures 5 and 6. The two conductors of each Lecher system are indicated by *a*; *b* are the short-circuiting bridges, which are moved by means of the screw rods *c* and the knobs *d*. *e* is a plate of insulation material. *D* is the measuring diode.

Δl which may not be considered as small compared with a quarter wave length formula (6) can no longer be applied. The decrease of the wave resistance ζ, which according to (6) would also make possible the measurement of a smaller value of R_x, is often incapable of being realized, since for a small wave resistance the two conductors of the Lecher system must be very close together, which usually leads to mechanical difficulties.

Resistances which are at least several times smaller than the wave resistance can be measured by connecting them with the measuring apparatus with the intermediate connection of a Lecher system having the length of a quarter wave length. As was stated in the article cited in footnote 5), such a Lecher system may be considered as a transformer which transforms an impedance Z into an impedance ζ^2/Z. A resistance which is a given number of times smaller than the wave resistance ζ is thus transformed with such a transformer into a resistance which is the same number of times larger than the wave resistance. Actually the introduction of this transformation Lecher system comes down to the use of a Lecher system closed at one end one *half* wave length long.

It is obvious that the precautions against the occurrence of systematic measuring errors, which were already mentioned in the case of measurements at wave lengths above 1 m, are even more necessary at decimetre wave lengths. Careful attention should be paid to keeping the connections very short. Where for technical reasons a connection cannot be made short enough, in interpreting the results

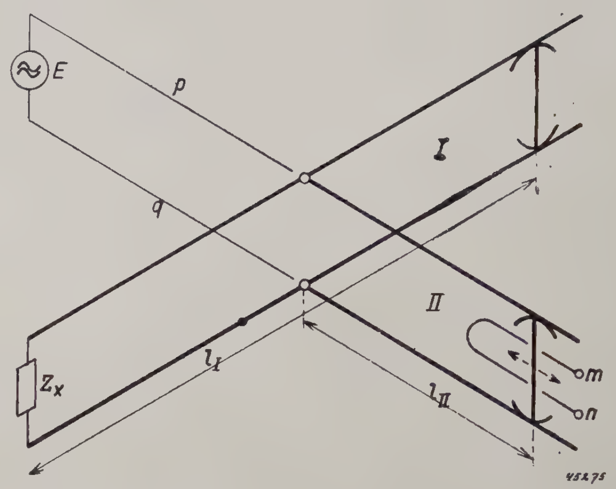

Fig. 8. An impedance Z_x which is small compared with the wave-resistance can be measured by the aid of a Lecher system the lenght of which amounts to about half a wave length. The coupling of the measuring transmitters L_1 and the connection of the auxiliary Lecher system II take place in the middle of the Lecher system I.

of the measurement account must be taken of the presence of this connection. With the very compact assembly which is necessary for decimetre waves it is often impossible to introduce a condenser to compensate the self-induction of a connection.

[8]) An upper limit is set by the accuracy with which Δl can be determined.

AN APPARATUS FOR STROBOSCOPIC OBSERVATION

by S. L. de BRUIN.

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When a condenser is discharged through a gas-discharge lamp, a light flash of short duration and high intensity is obtained. In this manner it is possible to make a source of light which is suitable for stroboscopic observations and for the photography of rapidly moving objects.

A description is given in this article of a stroboscope developed by Philips, consisting of a tube filled with rare gas as gas-discharge lamp and an electrical apparatus for the condenser discharges. The latter furnish periodically repeated current impulses of 2000 A at time intervals which can be varied between 2 sec. and 1/250 sec. The light flashes hereby excited have an intensity of about 200 lumen seconds with a maximum light flux of 2×10^6 Dlm (duration 10^{-5} sec.). The period of the light flashes can be synchronized in many ways with the phenomenon to be investigated, so that numerous possibilities of application exist, which are illustrated by means of a few examples.

If one compares the performance of a piece of modern optical apparatus with that of the human eye it will be found that nature still leads technology in sensitivity, but that the technical devices offer the advantage of a much higher velocity and greater precision. The eye is unable to follow phenomena which take place in less than $^1/_{10}$ second. Rotational motions of more than 3 or 4 revolutions per second can no longer be clearly seen, while in the case of translation at a speed of more than 5 m/sec, seen from a distance of 1 m, the image already becomes so indefinite that there can be no question of exact observation.

Cameras with focal plane shutters can work approximately 100 times as fast, and in this way record phenomena which are invisible to direct observations. The velocity of about 0.001 second thus obtained still fails, however, to meet the requirements made in many technical investigations. With high-speed machines, for example, speeds up to 100 revolutions per second and translatory motion at speeds of up to 100 m/sec are not exceptional. If in the latter case it is desired to fix accurately the momentary situation of a part of a machine to within 1 mm, the observation may not last longer than 10^{-5} sec, and the moment of the observation must also be fixed accurately to within 10^{-5} sec.

A device commonly used to satisfy these requirements is the stroboscope. The action of the stroboscope is based upon the fact that it makes the objects to be investigated visible or photographable only at those moments at which the observation is desired. In the commonly occurring case in which these moments are repeated periodically there are simple devices. For example, a rotating disc with holes distributed at regular intervals around the circumference of a circle can be placed in the entrance pupil of a telescope. When this disc is rotated at the correct speed the successive holes will follow each other at such time intervals that the part of the machine which rotates or runs back and forth has executed exactly one cycle in that interval and is back again in the old position. The moving object is thus, as it were, fixed. Instead of fixing it, it may also be allowed to be displaced slowly, either forward or backward, by rotating the disc somewhat more slowly or more rapidly.

Another method of limiting the visibility of an object to certain periodically repeated moments consists in the use of a source of light which changes in intensity periodically. When a moving object is irradiated with such a light source the strongest visual impression is received at certain moments, so that by the correct choice of frequency and phase certain positions of the moving object can be emphasized. This stroboscopic effect of a source of light often occurs unintentionally when a machine which is driven by a synchronous motor is illuminated with a lamp which is fed from the same main as the synchronous motor. This phenomenon is most pronounced with certain gas-discharge lamps, which emit a very fluctuating radiation when fed with A.C. In the case of the arc light there is also a strong stroboscopic effect, while it is practically absent in the case of filament lamps.

In the case of non-periodic phenomena also the use of an intermittent light source offers improved possibilities of observation. A familiar experiment is the observation of an induction machine (Wimshurst machine) by the light of the jumping spark. The duration of the electrical flashover is so short that the discs of the machine seem to stand still. It is striking that the inertia of the eye here forms no hindrance; apparently the eye can receive a visual impression within any given short

time interval provided the total amount of light is sufficient and the eye has time enough after the flash to assimilate the impression.

The light of a spark is also very suitable for photographing a moving object. In this way it is easily possible to reduce the exposure time to 10^{-5} or 10^{-6} sec. It is less easy to fix also with this precision the moment at which the exposure takes place. It depends upon the nature of the phenomenon to be observed what devices must be used; mechanical, photoelectrical or acoustic devices can be employed.

In the following an apparatus will be described which is suitable for stroboscopic examination in laboratories and factories. This apparatus, type GM 5500, is so designed that a single flash as well as periodically repeated flashes can be obtained. The time interval between the flashes can be adjusted within wide limits, and the generator which excites the flashes can be synchronized with the part of the machine to be observed. The light intensity of the flashes is so great that the apparatus can be used at the brightness normally present in a room in the daytime without hindrance from the continuous light.

The flash lamp

As already stated above, the flash of an electric discharge is used. Now for a permanent set-up it is undesirable that the spark should occur in air, because the electrodes would be too strongly attacked. The obvious solution is to use a rare gas instead of air. The spark gap is thus constructed as a discharge lamp filled with a rare gas.

The best results were obtained with argon at a high pressure. The higher the pressure, the greater the intensity of the light of the flashover. A limit is set to the pressure by the requirement that the flashover voltage may not be too high and that a reasonable lifetime must be ensured for the lamp.

The light of the high-pressure argon lamp is a bluish white and has a continuous spectrum with a high photographic actinity. It thus shows some resemblance to a water-cooled mercury lamp, which could also be used as flash lamp. However, due to the fact that there is no necessity for water-cooling, the argon lamp is easier to handle and, moreover, possesses various advantages compared with the mercury lamp: it is always ready for use, while in order to obtain the necessary vapour pressure the mercury lamp must first be warmed, and it has a shorter flash time, since the light emission of the mercury lamp is not only an electrical phenomenon but in part also a thermal phenomenon, so that there is a certain phosphorescence due to the heat inertia of the mercury vapour.

After a detailed investigation of the most favourable combination of gas pressure, separation of electrodes and tube dimensions, a lamp with very good technical characteristics was successfully designed. The flash time amounts to about 10^{-5} sec; within this time an amount of light of 200 lumen seconds is emitted and an energy of 2 W sec. consumed, so that the specific light flux amounts to 100 lm/W. This is about the same efficiency as can be obtained under favourable conditions with a water-cooled mercury lamp of very high pressure.

The light flux during the flash is about 2×10^6 Dlm with a current of 2000 A and a power of 200 kW. In addition to these very high peak loads the lamp also receives a small continuous load in order to facilitate the breakdown. The total energy consumption of the lamp is about 75 W at, for example, 25 flashes per second.

The tube of the lamp consists of quartz and is mounted in a nitrogen-filled bulb. The nitrogen filling is necessary, since with air filling the exterior of the hot quartz tube would be attacked by the atomic oxygen which is formed due to the ionizing action of the ultraviolet radiation of the lamp.

The rear of the bulb is covered on the inside with a mirror and concentrates the light beam in a relatively small solid angle, so that an amplification of the illumination of about 75 times is obtained in the axis of the beam. At a distance of 2 m from the lamp the peak value of the illumination intensity at the axis is about 10^7 lux, which is sufficient for photography even with a strongly diaphragmed lens in the available time of 10^{-5} sec. The photographs given further on in this article were made with diaphragms F/16-F/22, so that it was possible to place the camera close to the object and still obtain great depth of focus.

In *fig. 1* the stroboscope is shown. The lamp is mounted in a rotating holder which is connected by means of a high-tension cable with a cabinet on wheels containing the electrical apparatus. The light distribution of the stroboscope lamp is reproduced in *fig. 2*.

The electrical apparatus

From the description of the flash lamp it has become apparent that the electrical apparatus must furnish current impulses of 2000 A and with a duration of 10^{-5} sec. Depending upon the appli-

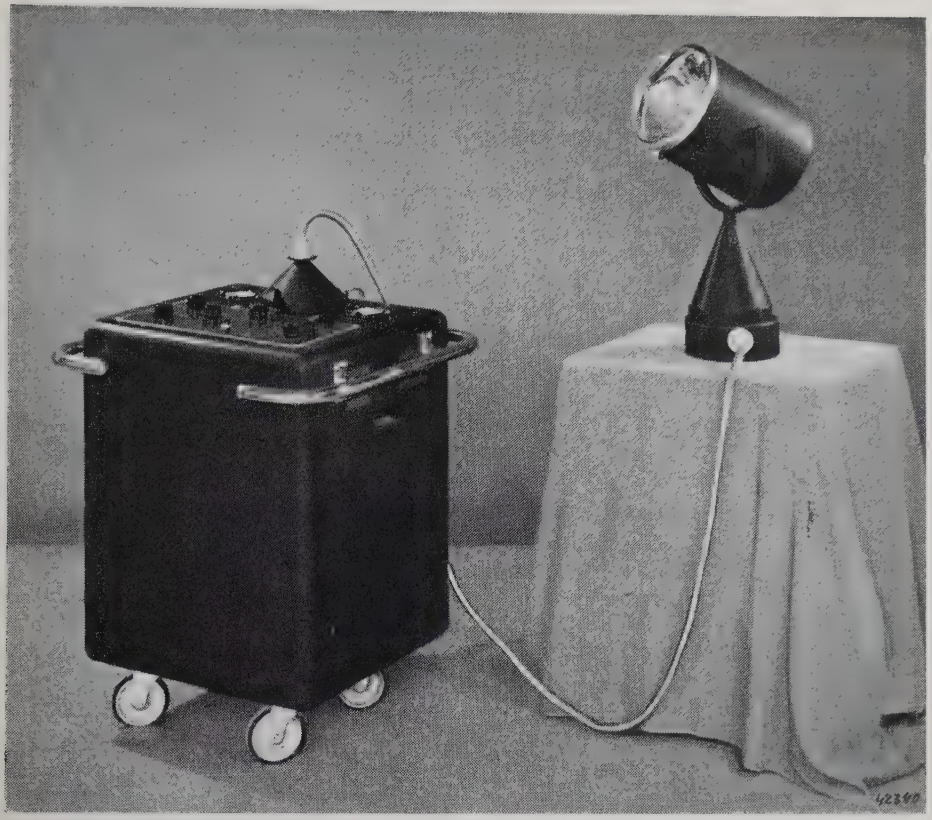


Fig. 1. The Philips stroboscope GM 5500.

required. The frequency at which these impulses, which are excited by a separate generator, are repeated can be regulated between 0.5 c/sec (30 impulses/min) and 250 c/sec (15 000 impulses/min). Moreover, it is possible to synchronize the impulses with a voltage led in from the outside. Finally the apparatus contains an electrical frequency meter which is coupled with the control generator.

We shall now describe successively the chief components of the apparatus.

The supply generator for the flash lamp

The connections for the supply generator for the flash lamp are given in *fig. 3*. *Via* a charging resistance R_1 a condenser C_1 is gradually charged to 600 V in order to be discharged again at certain moments *via* the relay valve and the flash lamp A, producing thereby the required current impulses.

As already discussed, the relay valve must be able to deal with several thousand amperes, while the average current amounts to less than 1 ampere. Taking into account these very abnormal conditions of use, a valve of special construction was designed and is shown diagrammatically in *fig. 4*. In connection with the low average load the dimensions of this valve were chosen relatively small, so that at each breakdown the electrodes are heavily overloaded. This overloading however, has no harmful results since both electrodes consist of mercury. Only an intense evaporation of the mercury occurs during the current impulse. The vapour

cation it may be desirable to obtain single or periodically repeated discharges, while in every case it is important to be able to synchronize the moment of the breakdown with the phenomenon to be observed.

For feeding the flash lamp we use connections with a relay valve which is ignited by a voltage impulse at the moments at which the discharges are

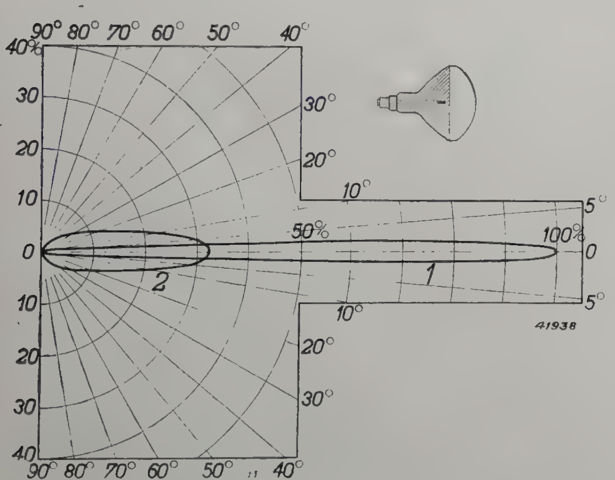


Fig. 2. Distribution of the light intensity of the stroboscope lamp, *1*) with a clear, *2*) with a frosted bulb. The rear wall of the bulb is covered with a mirror in both cases. The scale of curve *2* is 10 times as large as that of curve *1*, so that the maximum light intensity for the clear bulb is about 30 times as great as for the frosted bulb.

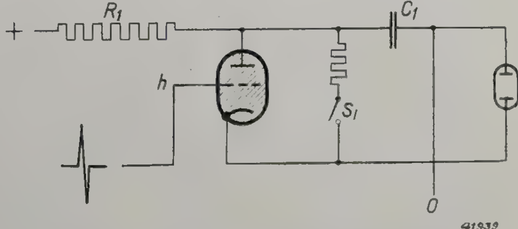


Fig. 3. Connections for the supply of the flash lamp A by means of a condenser and a relay valve.

condenses in the glass domes over the electrodes and the condensed mercury drips back to the electrodes.

For the ignition of the relay valve an auxiliary electrode h is introduced at the cathode side, which upon application of a voltage impulse (about 8 kV), causes the occurrence of a cathode spot and thus initiates the discharge. The condenser is then discharged *via* the relay valve and the flash lamp, whereupon the relay is extinguished. If due to the current supplied *via* the charging resistance R_1 the relay valve should continue to burn, it may be extinguished by practically short-circuiting it during a short time by means of the switch S_1.

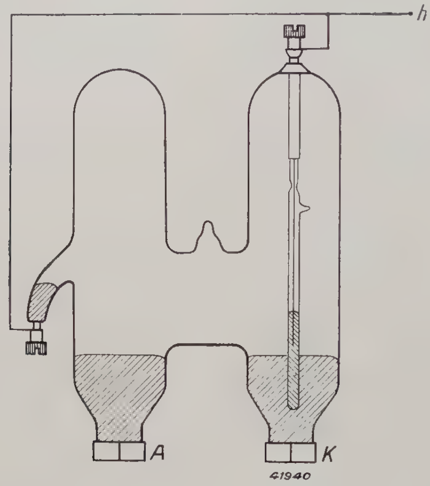


Fig. 4. Construction of the relay valve for the supply of the flash lamp. The electrodes are of mercury and can tolerate short-lived current impulses of 2000 A. For the ignition of the valve a voltage of a few thousand volts must be applied to the auxiliary electrode h.

According to the employment of the stroboscope there are different ways of synchronising the voltage impulses which serve to ignite the relay valve, namely:

a) with the AC voltage of the supply mains,
b) with an AC voltage or voltage impulse of about 50 V from the outside,
c) mechanically, by breaking a contact,
d) mechanically, by making a contact; this is also used for electrical synchronization with a single voltage impulse.

In order to obtain the synchronization voltages in the case of non-periodic phenomena, use may be made of a microphone or a photocell. Since these apparatuses only give minimum voltages or currents, it is of course necessary to employ a suitable amplifier.

As an illustration of this method of procedure a set-up for the photography of the collision between

Fig. 5. Arrangement for photographing the collision between tennis ball and racket with the help of the stroboscope. The illumination is synchronized by means of a microphone.

a tennis ball and a racket is reproduced in *fig. 5*. The synchronization is here obtained by means of a microphone which reacts to the ping of the collision. The greater the distance between racket and microphone the greater the difference in time between collision and moment of exposure. This may be seen in *fig. 6*: exposure *a*) was made with a distance of only a few decimetres, while in the case of exposure *b*) the distance was more than a metre. In the first case the moment of contact was recorded, while in the latter case at the moment of exposure the ball had already rebounded several centimetres.

The frequency metre

In order to be able to control accurately the number of flashes per second furnished by the stroboscope, the apparatus is provided with a frequencymeter. This instrument measures the frequency indirectly by indicating the average charging current of a condenser which is discharged at each flash through the gas triode, to be charged again afterwards to a certain voltage. *Fig. 7* shows the principle of the connections.

The gas triode of the frequencymeter is controlled by voltageimpulses which are taken from the same impulsevoltage of 8 kV with which the relay valve of the supply generator is controlled. In addition to this impulsevoltage there is also on the grid of the gas triode a negative bias of such a magnitude that in the absence of an impulse no breakdown can occur. Since at every breakdown the condenser is almost completely discharged, the average current through the gas triode is equal to the charge of the condenser multiplied by the frequency of the voltage impulses. This current is indicated by a rotating coil instrument which is calibrated directly in number of flashes per minute.

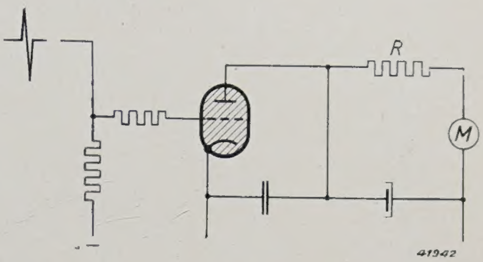
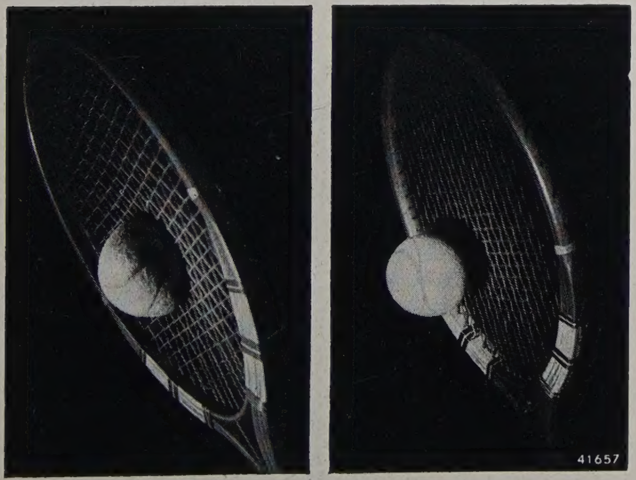


Fig. 7. Connections of the frequencymeter. The gas triode is blocked by a high negative voltage and only breaks down when a voltage impulse acts on the terminals which are connected with the output of the control generator. The meter M measures the number of discharges per second of the condenser.



a *b*

Fig. 6. Two photographs of the collision between tennis ball and racket.
a) Distance of the microphone a few decimetres;
b) Distance of the microphone several metres.

Applications

In visual observation the stroboscope is especially suitable for rapid, often orientating observations. With the help of the frequency meter the frequencies of vibrations or other periodic movements can be determined. Interesting phenomena which occur in a certain phase of the motion being investigated can be recorded photographically, while photography is also capable of furnishing information about events which occur only once.

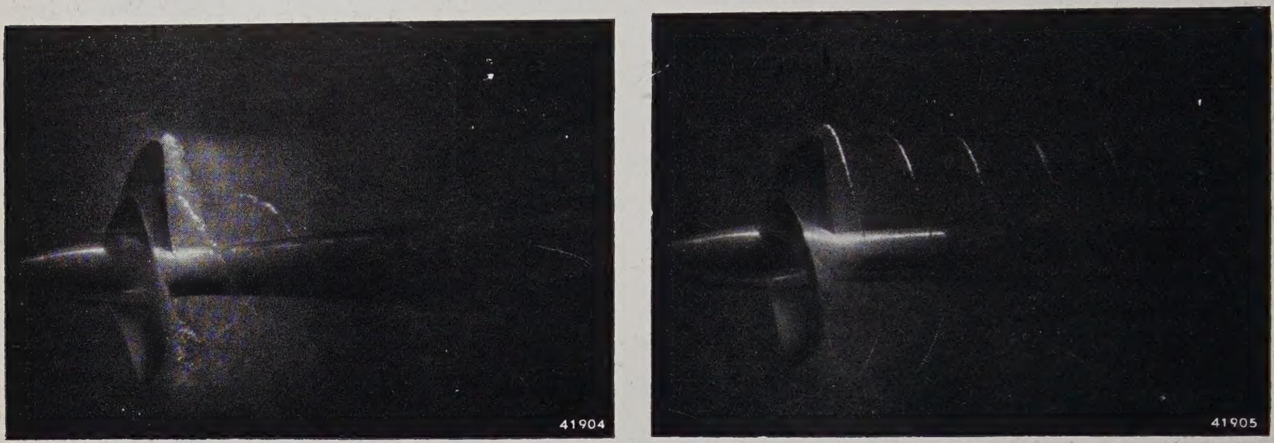
It is often possible immediately to interpret the photographs quantitatively. In the case of the examples discussed in the following, however, we shall omit this and only use the photographs for the characterization of the object observed.

Cavitation of ships' screws

In shipbuilding it is important to adapt the dimensions and shape of the screw to the entrance velocity and the static pressure of the surrounding water in order to avoid "cavitation". Cavitation is the phenomenon which takes place on the surface of the screw when locally and temporarily such a low pressure occurs that vapour or gas bubbles occur. These bubbles may implode on the surface of the blade of the screw, which is then exposed to the water hammer effect which may result in serious erosion of the material of the screw.

In order to study this phenomenon and to determine experimentally the best shape for the screw, models of screws are studied in a flow channel in which, by regulation of the velocity of the water, the water pressure and the number of revolutions,

the phenomenon of cavitation can be faithfully reproduced and its influence on the driving properties of the screw can be measured. This "cavitation tank" is provided with glass observation windows through which it is possible to illuminate the model srew stoboscopically and to observe and photograph the phenomenon of cavitation. *Fig. 8a* shows a ship's screw with strong cavitation, while in fig. 8*b* a screw with no cavitation is shown. The bright spiral line seen in the latter case is the top spiral of the screw.



a *b*

Fig. 8. Ship's screw in cavitation tank. *a*) Strong cavitation, *b*) no cavitation. The bright line in *b*) indicates the top spiral of the screw. The photographs were taken in the Naval Shipbuilding Testing Station in Wageningen.

The cutting by the teeth of a planing machine

In testing a planing machine it is important to know whether all the teeth take an equal share in the cutting process. This can easily be ascertained by observing the machine in action with the help of a stroboscope lamp. *Fig. 9* is a reproduction of a photograph which was made during such an investigation. This single photograph, which shows only one of the teeth in action, is naturally insufficient to permit the drawing of the desired conclusions.

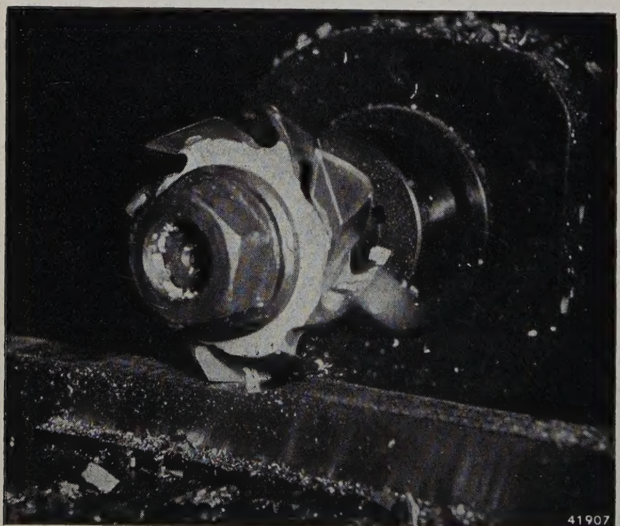


Fig. 9. Instantaneous photograph during the observation of a planing machine with the help of the stroboscope.

Investigation of internal combustion motors

In the case of high speed machines the stroboscope may be useful in checking certain parts. As an example a photograph is given in *fig. 10* of the valve

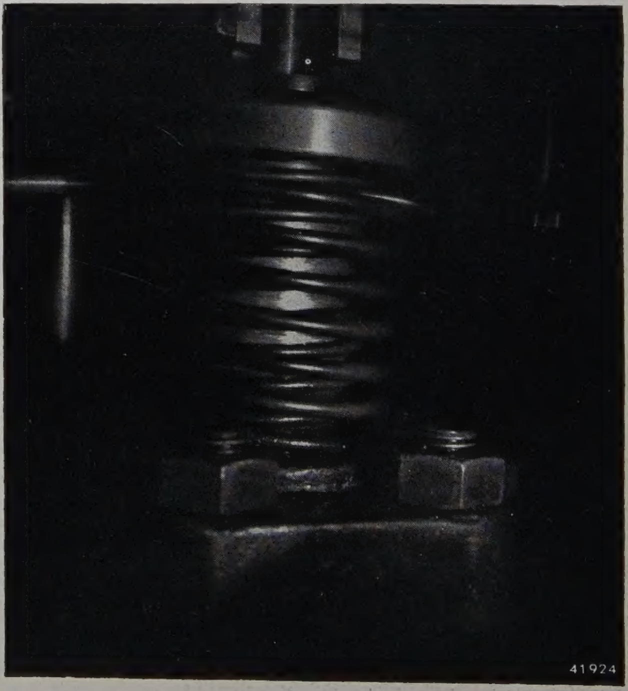


Fig. 10. Photograph during the observation of the valve springs of a Diesel motor with the help of the stroboscope.

Fig. 11*a*

Fig. 11. Photographs of water jets with light flashes from the stroboscope lamp. *a*) Jet from a faucet, *b*) jet from a douche.

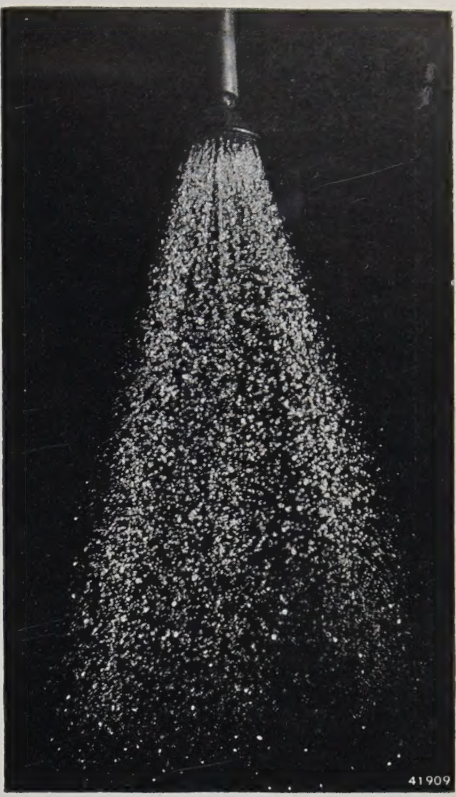


Fig. 11*b*

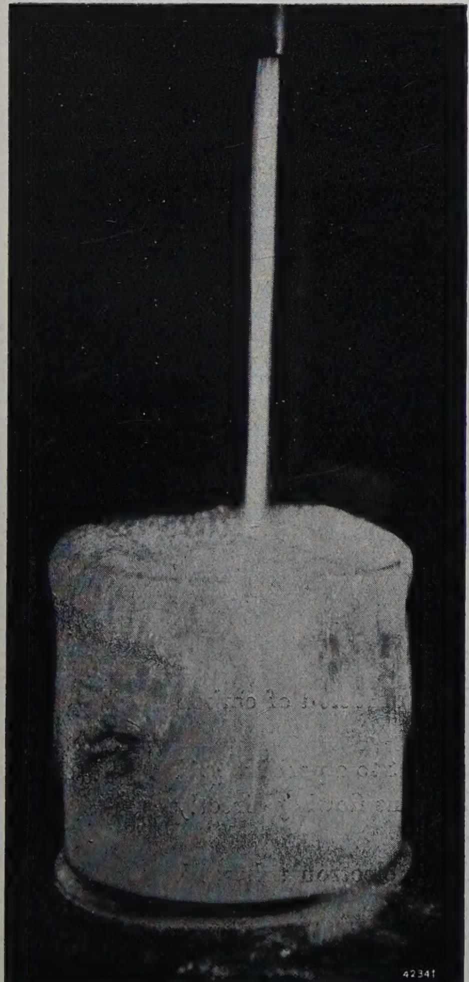


Fig. 12

Fig. 12. This photograph was made for the sake of comparison with fig. 11*a* with the help of a photoflash lamp. The flash time of the photoflash lamp is found to be many times too long for a sharp photograph of the foam.

springs of a Diesel motor. The stroboscopie observation of the valves springs is important, because, due to phenomena of inertia, the phase of the opening and closing of the valves may deviate at high speeds from the phase adjusted with the motor stationary.

Observation of liquids

In certain applications of the stroboscope no synchronization of the light flash is necessary and particular advantage is drawn from the short exposure time. An example of this is the investigation of water jets, illustrated in *fig. 11a* and *b* by the comparison of the jets of a faucet and a douche. It can clearly be seen that the foaming water from the faucet consists entirely of bubbles, which cannot be distinguished in the photograph reproduced in *fig. 12* taken for the sake of comparision with a photoflash lamp.

A practical application is found in the investigation of jets of liquid in the lubrication of machines for metal working. As an example in *fig. 13* a photograph of the lubrication of a centreless grinding machine is reproduced. It may be seen that the lubrication liquid is blown aside by the wind from the grindstone and thus does not flow over the grindstone as was intended. This observation led to a change in construction.

Other applications

In addition to these examples there are, of course, numerous other possible applications of the stroboscope. An extensive field is formed for example by the high-speed machines of the textile industry, such as spinning machines, looms, sewing machines, etc. A less obvious possibility of application is in

material testing, where advantage can be taken of the possibility of photographing at exactly the right moment, with the help of the stroboscope lamp, the very rapid process of the breaking of a piece of work.

In order to illustrate this possibility we reproduce as a final example in *fig. 14* an electric light bulb being broken with a hammer. The synchronization in this case was mechanical, by means of a thread which gives the synchronization impulse at the moment that it is broken by the descending hammer.

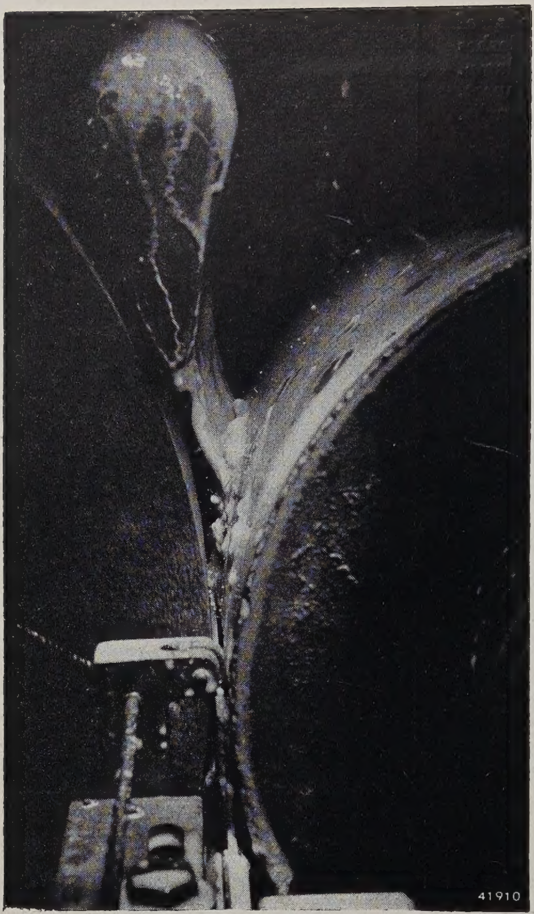


Fig. 13. Cooling of a centreless grinding machine. The lubricant is blown aside by the wind from the rotating grindstone.

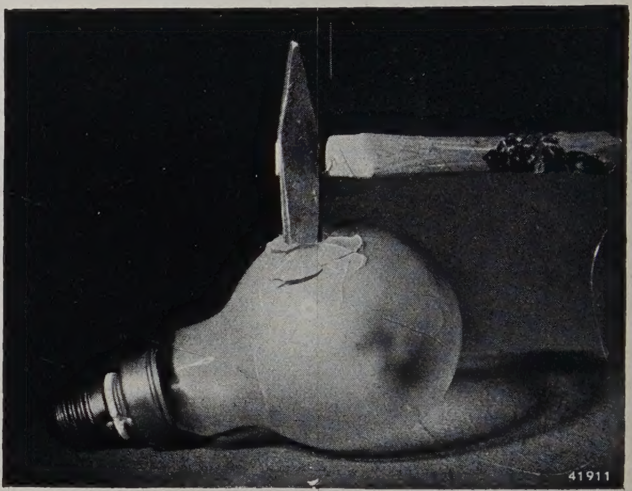


Fig. 14. Smashing an electric light bulb with a hammer. The synchronization of the photo was by means of the breaking of the thread which is fastened to the handle of the hammer.

Contents of *Philips Research Reports* 1, No. 1, 1946